December 22, 2015

Prof. Christopher A. Williams
Associate Editor
Biogeosciences

RE: Submission of a revised manuscript to Biogeosciences

Dear Prof. Williams,

We are pleased to submit the revised version of our manuscript bg-2015-430 to Biogeosciences. We first want to thank you and the reviewers for your time in assessing our manuscript. As you could see in our previous responses to the reviewers comments, we introduced substantial changes to address the issues raised regarding our Discussion paper: we modified the title, completely rewrote the Introduction, added a new Figure, removed an entire paragraph from the Discussion Section and the associated Figure, removed a Table and the associated text, and clarified the language in various places throughout the text. As you will see below, we performed additional changes to address the comments you provided following our initial responses.

Given that the impacts of fire on the global carbon cycle and climate are a topic of interest for a broad readership, we think that our study would fit particularly well in Biogeosciences, and we thank you for considering our revised manuscript.

Please find the following elements below:

- Our response to your Editor comments;
- The reproduction of our previous responses to Reviewer #1 and Reviewer #2, as uploaded on the website of Biogeosciences on December 8th. We noted two errors in our previous responses: 1) at the end of our response 2.3, we should have written that we removed former Fig. 8 (not former Fig. 3); and 2) in our response 2.9, we should have written "mimic" (not "mimick"; the correct spelling appears in our revised manuscript); and
- The 'track changes' version of our revised manuscript (there appears to be minor issues with tracking changes in the LaTeX package from Copernicus; in case of any doubt, please refer to the standard version of the revised manuscript that we also uploaded to Copernicus system, along with the current response). Due to the addition of a new Fig. 1, former Figs. 1–7 are now Figs. 2–8; since we removed former Fig. 8, Fig. 9 has not changed number.

Best regards,

Jean-Sébastien Landry
McGill University (now at Concordia University)

H. Damon Matthews
Concordia University

RESPONSE TO THE EDITOR

The Editor comments are in italics, with our responses given in a regular font.

Comments to the Author:

After looking over your responses to reviewer comments and the associated revisions you proposed I would encourage a re-submission. I agree with reviewers that, after some re-framing, the paper will make a valuable contribution to scientific understanding.

>> E.1 We thank you for encouraging a re-submission and are glad that you consider our manuscript as having the potential to make a valuable contribution to the field. Please see below how we re-framed various parts of the text to address your comments. <<

Reviewers agree that the narrative on impulse response functions as well as the paper's critiques about offline modeling approaches both need to be substantially altered. I would also tend to agree with reviewer comments raising concern about a lack a realism of a globally-punctuated large pulse of fire activity as a representation of the carbon-climate system response to the real fire process active in the earth system today. I see some value of such a model experiment to explore the fossil-vs-fire contrast, but wonder about how it translates to representing effects of a single, local fire event. It appears as though the proposed revisions will address some of these concerns, and encourage this direction.

>> E.2 We are happy to see that you agree with the revisions we proposed in our response 2.3 and which consisted of removing former Fig. 8, former Table 2, and the associated text in the Introduction, Results, Discussion, and Conclusions. <<

I do sense that proposed revisions may not fully address reviewer concerns regarding how the paper interprets and discusses the climate effect of co2 emissions from fire as if it is fundamentally different from that of fossil fuel emissions. It seems we all agree that the radiative effect of CO2 molecules from the two sources does not differ but this is idea gets somewhat twisted in the wording adopted in the original paper and seems to linger in the responses to comments. Post-fire recovery of carbon stocks does indeed alter the net and cumulative effects of these two co2 emissions processes by introducing an additional carbon sink mechanism in the case of fire, which acts in addition to the land and ocean sinks that sequester CO2 emitted from fire or fossil fuel combustion sources alike. The fire process also alters land surface albedo and has an associated effect on climate, as you have simulated, however this effect seems to be interpreted as implicitly altering the effect of fire-derived CO2 emissions. This conflates two different process level effects that reviewers and I seem to agree should be kept separate. In my opinion these critiques go beyond issues of semantics and there may be need for further consideration to arrive at accurate and thoughtful wording in the revised paper.

>> E.3 We thank you for stimulating us to further improve our manuscript regarding the 'effect of CO_2 emissions' question. You will see below that we modified the Abstract and various parts of the text accordingly, and we hope you will consider the new wording more "*accurate and thoughtful*". However, we would like to state upfront that we think our main results—which appear in Figs. 3–5 and 7–8 (new numbering) and have not been disputed by the reviewers—do support the claim that CO_2 emissions from fossil fuel combustion have different effects on global carbon cycling and climate compared with the same

amount of fire-emitted CO_2. Indeed, we showed that a single pulse of fire led to changes in atmospheric, terrestrial, and oceanic CO_2 (Fig. 3) and temperature (Fig. 4a) that differed from the changes caused by fossil fuel CO_2 emissions that were equal to fire gross CO_2 emissions. Then, we showed (Fig. 5) that the changes still differed when the fossil fuel CO_2 emissions were equal to the net land-to-atmosphere CO_2 emissions caused by a fire pulse. Finally, we showed that the effects also differed for global carbon cycling (Figs. 7 and 8a) and temperature (Fig. 8b) following a stable change of fire regime; in this case, we only simulated fossil fuel CO_2 emissions equal to the net fire CO_2 emissions. Based on these results, considering that CO_2 emissions from fire vs. fossil fuel combustion have the same effects on the global carbon cycle and temperature is difficult to defend.

What seems to be the heart of the issue here is the (implicit) view that CO_2 emitted to the atmosphere should be conceived of as completely independent from its origin and fate, and from the concurrent changes in the climate system. Under this view and given that all CO_2 molecules are alike while being in the atmosphere (besides isotopic differences outside the scope of our study), our claim could appear inadequate. However, when understanding that different CO_2-emitting processes necessarily entail different atmospheric CO_2 lifetimes and different effects on albedo, one sees that there is actually nothing controversial about our claim. The regrowth flux necessarily involves a different behaviour for the CO_2 emitted by fire vs. fossil fuel (e.g., Fig. 3c), which necessarily means different effects on global carbon cycling and temperature. The opposite changes in land albedo (e.g., Fig. 4b) necessarily involve a different effect on global temperature, which then affects the carbon cycle itself (more on this below). Moreover, the fact that fossil fuel combustion involves a net addition of CO_2 to the atmospheric, terrestrial, and ocean pools necessarily leads to a different effect on the three global carbon pools compared to fire. Reviewer #1 stated that the "*effect of the emitted CO2 is the same* [...], *but what differs is the effect of the emitting process*". Our claim is slightly different: the effects of the emitted CO_2 on global carbon cycling and temperature differ **due to** the discrepancies (net addition of CO_2, atmospheric lifetime, and albedo) between the two emitting processes. We believe that this alternative claim is more helpful, because it recognizes that the CO_2 emissions should not be conceived of as if they were completely unrelated to the concurrent changes that necessarily result from the emitting process.

Our claim might provide a new angle, but this does not mean the claim is inadequate. A similar perspective is more established in the literature on the effects of land use and land cover changes (LULCC), even though this CO_2-emitting process does not result in a strong regrowth flux and is therefore more similar to fossil fuel combustion than fire is. For example, Arora and Boer (2010) noted: "*The direct injection of LUC emissions into the atmosphere of coupled climate carbon cycle models, with no corresponding changes at the land surface, does not take into account the associated albedo changes or the reduced capacity of the biosphere to sequester carbon, especially when natural vegetation is replaced with croplands.*" and later: "*LUC effects are sometimes introduced as an 'additional emission' term* [...] *estimated externally to the model and prescribed* [...] *in the same manner as the fossil fuel emissions* [...]. *This approach, however, compromises the interactiveness and interconnectedness of all of the components* [...]." Consequently, when simulating LULCC-caused CO_2 emissions explicitly, their effect on the climate is not the same as the effect from the same amount of fossil fuel CO_2 emissions (Simmons and Matthews, 2015). The only scientific controversy related to our claim was therefore related to its possible misinterpretation as implying different radiative effects for fire-emitted vs. fossil fuel-emitted atmospheric CO_2. We proposed in our previous responses a revision to clarify this issue; please see below how we improved this proposal.

Regarding the comment that the climatic effect from changes in land surface albedo and the fire-caused CO_2 emissions are "*two different process level effects that* [...] *should be kept separate*", we agree that additional simulations to separate these effects would provide interesting information and would allow to better understand the respective influences of the different fire-related processes involved. Nonetheless, please remember that the objectives of our study are not to provide in-depth analyses of all these processes, but to: 1) compare the long-term effects from fire vs. fossil fuel combustion; and 2) quantify the differences between gross and net fire emissions. In this context, accounting for the effect of albedo on the climate appears more advisable than neglecting it. The capacity of coupled models to estimate the impacts of temperature changes on land and ocean carbon cycling is one noteworthy progress of the past 15 years, even if the uncertainties remain large (Cox et al., 2000; Friedlingstein et al., 2006; Matthews, 2006; Arora et al., 2013; Friedlingstein et al., 2014). In our case, the albedo effect affects fire emissions because it changes vegetation productivity and soil–litter decomposition (through its impact on temperature), thereby modifying the amount of fuel affected by fire. The albedo effect also affects global carbon cycling by cooling the ocean, which increases CO_2 solubility. Once again, this is analogous that what appears in the LULCC literature. In their review of many previous studies on the CO_2 fluxes caused by LULCC, Pongratz et al. (2014) included not only the "instantaneous emissions" (akin to our gross emissions) and the "legacy fluxes" (akin to the decomposition of the fire-killed vegetation) in the "net LULCC flux", but also the effects of environmental changes caused by LULCC (albedo, etc.) on CO_2 exchanges (e.g., their Equations (13a–b) for studies performed in models similar to the UVic ESCM). Consequently, we believe that neglecting the effect of albedo changes on carbon cycling would actually decrease the value and comprehensiveness of our study.

Based on the previous considerations, here are the various additional improvements we included in the revised manuscript to address the spirit of your comment.

- We modified the beginning of our Abstract to start on a better foot, further addressing the 'coupled climate monopoly' issue raised by both reviewers. The modified text reads: "Fire is arguably the most influential natural disturbance in terrestrial ecosystems, thereby playing a major role in carbon exchanges and affecting many climatic processes. ~~Nevertheless, fire has not been the subject of dedicated studies in coupled climate-carbon models with interactive vegetation until very recently. Hence, previous studies resorted to results from simulations of fossil fuel emissions to estimate the effects of fire-induced CO_2 emissions. While atmospheric CO_2 molecules are all alike, fundamental differences in their origin suggest that the effects from fire emissions on the global carbon cycle and temperature are irreconcilable with the effects from fossil fuel emissions.~~ *While in the atmosphere, fire-emitted CO_2 has the same radiative effect as fossil fuel-emitted CO_2. However, major differences exist between the effects of fire vs. fossil fuel combustion on the global carbon cycle and climate, because: 1) fossil fuel combustion implies a net transfer of carbon from geological reservoirs to the atmospheric, oceanic, and terrestrial pools, whereas fire does not; 2) the atmospheric lifetime of fire-emitted CO_2 is not the same as for fossil fuel-emitted CO_2; and 3) other impacts, for example on land surface albedo, also differ between fire and fossil fuel combustion.* The main purpose of this study is to illustrate the consequences from these fundamental differences between ~~CO_2 emissions from~~ fossil fuel~~s~~ *combustion* and non-deforestation fires [. . .]."

- Also in the Abstract, we removed the part of a sentence that referred to gross emissions: "Our results also support the notion that most net emissions occur relatively soon after fire regime shifts and then progressively approach zero~~, whereas gross emissions stabilize around a new value that is a poor indicator of the cumulative net emissions caused by the fire regime shift~~."

- In the revised Introduction, we improved the part of the text explaining the differences between CO_2 emissions from fire vs. fossil fuel combustion: "For ~~a given~~*the same* amount of emitted CO_2, fire therefore differs from fossil fuel combustion in terms of: *1) the net addition of CO_2 to the active carbon cycling pools for fossil fuel combustion only;* ~~1~~*2*) average lifetime of CO_2 molecules in the atmosphere; and ~~2~~*3*) non-CO_2 climatic impacts *(e.g., albedo) that also affect the carbon cycle. Given that these differences are in fact inseparable from the CO_2 emitting process, we expect the same amount of CO_2 emissions from fire vs. fossil fuel combustion to have different effects* *on the global carbon cycle and temperature.* ~~When comparing fire with fossil fuel combustion, the expression "CO_2 emissions" will henceforth implicitly include the consequences from these differences in atmospheric lifetime and surface albedo.~~"

- We performed various modifications to 'tune down' or clarify the issue of different effects from CO_2 emitted by fire vs. fossil fuel combustion.
  - p15195, starting on l9: "These differences ~~in the effects from fire vs. fossil fuel emissions on the carbon cycle~~ then affected the global mean atmospheric surface temperature [. . .]."
  - p15195, starting on l25: "All previous outcomes illustrate that the effects *on the global carbon cycle and temperature* from fire vs. fossil fuel CO_2 emissions differ ~~fundamentally~~ for identical pulse magnitude defined in terms of gross (i.e., combustion only) fire emissions."
  - p15196, starting on l19: "The previous results ~~provide relevant information regarding fundamental differences between fire and fossil fuel CO_2 emissions, but~~ were based on single pulses of fire activity~~. We~~*; we* now turn to stable fire regimes for which [. . .]. <<

As another point, I would suggest that emissions from decomposition of fire-killed biomass are a component of "fire emissions" being the result of the fire process albeit not from direct combustion, and I would encourage additional consideration of how that should be framed in the paper's revised version.

>> E.4 We agree that the decomposition of the fire-killed, but uncombusted, vegetation is part of fire net CO_2 emissions. In fact, this decomposition flux is a major component of initial fire emissions, explaining (as we noted in the Results) why the atmospheric CO_2 anomaly reaches values higher than would result from gross emissions only. Going beyond this observation would require additional work and simulations to track the proportion of net emissions resulting from this decomposition flux, which is outside the scope of the current study. The Abstract, Methods, and revised Introduction mentioned that this decomposition flux is part of fire net emissions, but the text might not have been clear enough. To clarify this point, we modified the following sentence in the revised Introduction: "A second objective is to quantify the differences between gross and net fire CO_2 emissions over 1000 years following major changes in fire frequency*; note that the simulated net emissions accounted for all processes mentioned previously (i.e., decomposition of fire-killed vegetation, regrowth, global CO_2 fertilization, and temperature–CO_2 interactions on land and in the ocean) in addition to the gross (i.e., combustion) emissions.*"

Finally, please note that we included the modifications listed below, as well as few minor corrections.

- We improved the first sentence of the revised Introduction: "Fossil fuel emissions entail a net transfer of ~~CO_2~~*carbon* from geological reservoirs to [. . .]".
- In the revised Introduction, we improved the sentence justifying the use of a coupled climate model: "Using such a model allowed us to *keep track of the total carbon in the Earth System, include the major role of the ocean in the fate of the fire-emitted CO_2, and* account for the various feedbacks mentioned previously (i.e., CO_2 fertilization and temperature–CO_2 interactions)*, which are consequential for the global carbon cycle and temperature responses*~~, as well as the major role of the ocean in the fate of the fire-emitted CO_2~~."
- In the Methods (p15192, starting on l14), we removed the following sentence to avoid repetition with the previous modification to the Introduction: "In addition to the CO_2 released by combustion, net fire emissions included post-fire vegetation regrowth, decomposition of the vegetation that was killed but not combusted, CO_2 fertilization, and climate–carbon feedbacks."

- In the same Methods paragraph, we included a clarification: “We then injected into the atmosphere yearly fossil fuel CO_2 emissions that were equal to these net fire emissions, including when they were negative *(implying atmospheric carbon was sequestered back into geological reservoirs)*.”

- We improved the following sentence in the Results (p15194, starting on l21): “Finally, fractional changes greater than 1.0 were observed for the atmosphere and land shortly after the pulses because ~~the net emissions (i.e., including~~*, due to* the decomposition of the uncombusted vegetation killed by fire~~)~~*, the net emissions* were ~~initially~~ higher than the gross emissions upon which the magnitude of the pulses were defined.”

- p15196, starting on l5: “[. . .] whereas for fire the net emissions already accounted, by definition, for vegetation regrowth*, global CO_2 fertilization,* and all climate–carbon feedbacks.”

- To better address the comment from the reviewers about too much emphasis on the gross emissions, we deleted the following text (p15197, starting on l21): “The cumulative gross emissions at the end of the simulations were around 8, 23, and 21 Eg C for Fire20S, Fire100S, and Fire200S, respectively. These values were much higher than the corresponding cumulative net emissions (Fig. 5 and Table 3) – and, for the two most severe regimes, were in fact even higher than the estimated fossil fuel total resource base (Stewart and Weaver, 2012). The injection of such amounts of fossil fuel CO_2 into the atmosphere would obviously result in much more severe impacts on the carbon cycle and temperature (Matthews and Caldeira, 2008; Archer et al., 2009; Eby et al., 2009; Joos et al., 2013) than were observed for the three stable fire regimes.”

- p15198, starting on l17: “As was the case for the pulse simulations (see Sect. 3.2), this ~~opposite~~ *different* effect ~~of fire vs. fossil fuel emissions~~ on T_{s} ~~was related to~~*came from opposite* changes in land albedo [. . .].”

- p15199, starting on l7: “~~The~~*Fire activity not only leads to CO_2 emissions through the* combustion of land carbon and the further decomposition of killed but uncombusted vegetation ~~constitute not only sources of fire emissions~~, but also decrease*s* the amount of vegetation that can instantaneously be fertilized by the fire-induced increase in atmospheric CO_2.”

- p15199, starting on l12: “Third, these contrasting effects on terrestrial vegetation mean ~~opposing~~ *opposite* changes in land albedo [. . .].”

- p15203, starting on l22: “[. . .] with the ~~opposing~~*opposite* changes in land surface albedo further compounding these discrepancies [. . .].”

- p15204, starting on l12: “[. . .] most of the net emissions actually occurred relatively quickly after the regime shift and ~~net emissions~~ progressively decreased to almost zero [. . .]”.

- To further address the comment from the reviewers about too much emphasis on the gross emissions, we deleted the following text (p15204, starting on l14): “These results illustrate how inadequate it would be to represent the effects of fire regime changes by fossil fuel CO_2 emissions equal to gross fire emissions.”

- We deleted the following sentence (p15204, starting on l22): “Yet many studies of fire effects on these crucial elements have resorted to simulations of fossil fuel emissions in climate models.”

- In the legend of Fig. 7 (new numbering): “Fossil fuel emissions, which were set equal to net *yearly* fire emissions.”

- In the legend of Fig. 8 (new numbering): “The fossil fuel emissions were set equal to net *yearly* fire emissions.” <<

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Review #1: please note that the review of our manuscript is in italics, with our responses given in a regular font.

General remarks:

The manuscript by Landry and Matthews entitled "Fire vs. fossil fuel: all CO2 emissions are not created equal" is a welcome addition to the literature on simplified carbon cycle response models based on more complex models, with the interesting difference that it does not consider a particular new part of the carbon cycle, but that it distinguishes between to combustion processes and their effects on the carbon balance of the terrestrial biosphere. This to my knowledge is a new angle on the problem that seems suitable for publication in Biogeosciences. However, I have some serious concerns about presentation which, if not addressed fully, will in my opinion rather reduce than increase clarity and impact. I am trying to detail this in the following comments. At times, I also find that there is a lack of clear definitions, which should be addressed through substantial revisions of the introduction and methods sections. What also seems to have been lost is a discussion of the vastly different scales between direct impacts of vegetation fires at the plot scale, regional impacts of albedo changes, and the diffuse impact of increasing or decreasing CO2 via CO2 fertilisation that acts only at a global scale due to the fast mixing time of the atmosphere.

>> 1.1 We thank you for your time and numerous comments that helped us improve our manuscript. We appreciate that you qualify it as a "*welcome addition*" and note that you did not have any issue with the results per se, although you suggested many changes to the presentation. As you will see below, we substantially modified the text to address the issues you raised. We feel that many of the concerns you expressed come down to the exact meaning one gives to the expression "CO_2 emissions". We of course agree, and already stated in the Abstract, that all CO_2 molecules in the atmosphere have the same effect. However, differences between fire and fossil fuel combustion imply, from the moment when CO_2 emissions are created, the existence of unequal non-CO_2 climatic effects (we considered albedo in this study) and a different atmospheric lifetime for the CO_2 emitted. Based on your comments, we believe that you agree with this view, but had issues with the way we expressed it; we therefore strove to reformulate the text along your suggestions. We also added to the Introduction the various spatial scales associated with different impacts, to address the last sentence of your comment (please note that we considerably modified the Introduction to address various comments, the revised version appearing at the end of our response). <<

Major comments:

(1) The fact that much of the carbon (not CO2) emissions of wildfires is consequently taken up again by the biosphere is by no means new. This manuscript is in large parts written as if it was.

>> 1.2 We agree that this idea is by no means new and did not want to take credit for it. This is why the second paragraph of our former Introduction presented previous studies, going back to year 1980, that aimed to quantify the net effect of fire on global land carbon storage. The new contribution of our study consists of quantifying this net effect in a coupled climate–carbon model with interactive vegetation, thereby accounting for effects that were neglected in previous global-scale studies (e.g., fire-induced CO_2 fertilization). To clarify this point, we substantially revised a sentence in the Introduction, which now reads: "~~The latter two studies were however performed~~ *While the fact that vegetation regrowth offsets a fraction of gross fire emissions has been appreciated for some time, previous global quantifications of the difference between gross and net emissions have been performed with first-order estimates (Seiler and Crutzen, 1980) or* in offline terrestrial models *(Ward et al., 2012; Li et al., 2014)*~~, and were therefore~~

~~unable to account for various climate–fire feedbacks, including fire-induced CO_2 fertilization and the impact of changes in surface albedo on temperature~~ *and have neglected relevant processes.*" Please note that the difference between net and gross fire emissions goes beyond vegetation regrowth, which we clarified by adding the following text after the sentence just quoted: "Indeed, net fire CO_2 emissions differ from gross emissions because they include not only the gradual decomposition of the non-trivial fraction of vegetation killed by fire but not combusted (especially for trees) and the post-fire vegetation regrowth, but also the effects of various feedbacks like the fire-induced CO_2 fertilization of terrestrial vegetation, or the impacts on vegetation productivity and soil–litter decomposition of temperature changes caused by modified atmospheric CO_2 and surface albedo." <<

Furthermore, the central result of this manuscript, e.g. presented on p. 15198, line 24ff "In this study, we have shown a consistent pattern of fundamental differences between the carbon cycle and climate effects of CO2 emitted by fire as compared to fossil fuel combustion" is simply wrong, which leads to significant confusion. The effect of the emitted CO2 is the same (e.g. if you had a power station next to an active forest fire, you could not distinguish between the effect of the CO2 coming from each one), but what differs is the effect of the emitting process, i.e. the fire in the combustion chamber (or whatever) vs. the grass, shrub or forest fire, including the involved flux of carbon. This confusion comes apparent in a sentence following within the same paragraph (p. 15199, l7) "Fire, on the other hand, gives rise to a much more dynamic land carbon response." Here, it is not the CO2 that is talked about, but the fire. My suspicion is that this confusion is deliberate in order to enhance the apparent urgency and novelty of the research results. I believe that this general thrust of the manuscript needs to be revised substantially.

>> 1.3 We thank you for raising this point, which boils down to a semantic issue that we clarified. For us, "CO_2 emissions" or "CO_2 emitted" in expressions like the "effects of CO_2 emitted by fire [or] fossil fuel combustion" implicitly included the fate of the atmospheric CO_2 molecules and the non-CO_2 impacts (e.g., changes in surface albedo) that accompany these emissions. So even though the radiative effect of each atmospheric CO_2 molecule is the same, one can easily distinguish a fire event from a power station through field and satellite observations of changes in albedo and vegetation. We clarified this semantic issue by adding two sentences to the Introduction: "For a given amount of emitted CO_2, fire therefore differs from fossil fuel combustion in terms of: 1) average lifetime of CO_2 molecules in the atmosphere; and 2) non-CO_2 climatic impacts. When comparing fire with fossil fuel combustion, the expression "CO_2 emissions" will henceforth implicitly include the consequences from these differences in atmospheric lifetime and surface albedo." We also clarified accordingly the first sentence cited in the comment (new text in italics): "In this study, we have shown a consistent pattern of fundamental differences between the carbon cycle and climate effects of CO_2 emitted by fire as compared to fossil fuel combustion*, which ultimately came from the net addition of CO_2 by fossil fuel combustion (contrary to fire), as well as the differences in atmospheric lifetime of emitted CO_2 and in non-CO_2 climatic impacts.*" Concerning the second sentence cited in the comment ("Fire, on the other hand, gives rise to a much more dynamic land carbon response."), it actually refers to the impact of fire on land–atmosphere CO_2 dynamics, contrasting it with the impact of fossil fuel (i.e., CO_2 fertilization only). We consider this sentence to be adequate. <<

For that reason, in order to make this manuscript publishable with BG, I argue that the title should be changed in order to avoid confusing semantics: it is not the "CO2 emissions" that is different, in the sense of "emitted CO2", but the "act" of emission. I know that this is very subtle, but as argued before, gives rise to just the confusion I referred to, leading to the impression of the reader that what is reported here is largely unknown and novel (which it isn't). A further note is that fossil-fuel burning is also a *form of fire, so that a further distinction needs to be made. I would suggest a title along the lines of "Carbon cycle impacts of wildfire vs. fossil fuel emissions", or "The fate of emitted CO2 from wildfires and fossil-fuel combustion".*

>> 1.4 Our previous title read "Fire vs. fossil fuel: all CO_2 emissions are not created equal", in which the word "created" already made the point raised above about the "*act*" of emission. The fourth sentence of our original Abstract further made this point more explicitly: "While atmospheric CO_2 molecules are all alike, fundamental differences in their origin suggest that the effects from fire emissions on the global carbon cycle and temperature are irreconcilable with the effects from fossil fuel emissions." We nevertheless revised the title to: "Fire vs. fossil fuel combustion: the source of CO_2 emissions affects the global carbon cycle and climate responses". Concerning your "*further note*", we agree that CO_2 emissions from fire and fossil fuel both involve combustion, but we do not see the added value in distinguishing 'fire burning' from 'fossil fuel burning' on this basis. <<

In agreement with this, I would also like to see the last sentence of the Abstract changed. In particular I object to the use of the word "ersatz results", which unduly belittles compartmental approaches to quantifying the effect, and that in a study that does not report error bars. I am convinced that a perturbation-based, compartmental approach could deliver results with just the same level of confidence. I believe that this form of presentation is unfair, too absolute and lacks scientific modesty by over-emphasizing the significance of the result of a study based on a single model. To further increase clarity, and to avoid creating a false impression of novelty, instead of a "historical" introduction chronicling the development of approaches used in the various scientific communities, the manuscript should rather start by describing the current accepted state of knowledge: CO2 emitted from fossil-fuel combustion changes radiative forcing in the atmosphere, and leads to CO2 fertilisation on the land (leaving out the oceanic effects, like acidification). By contrast, wildfires lead rapid re-growth of vegetation leading to CO2 uptake, long-term changes in vegetation distribution and standing live biomass, changes in land surface albedo, plus the same effects of fossil-fuel emissions, but modified by the difference in net flux. The historical rundown on past and recent approaches can then follow.

>> 1.5 We thank you for this comment, as our previous text did not adequately reflect our idea. The last sentence of the Abstract previously read: "Overall, our study calls for the explicit representation of fire in climate models, rather than resorting to ersatz results coming from fossil fuel simulations, as a valuable step to foster a more accurate understanding of its impacts in the Earth system." The purpose of this sentence was not to state that only coupled climate–carbon models should be used to study fire, but that studying the impacts of fire on global carbon cycling and temperature should be based on the explicit representation of fire. The new version of the sentence now reads: "Overall, our study calls for the explicit representation of fire activity as a valuable step to foster a more accurate understanding of its impacts on global carbon cycling and temperature, compared to conceiving fire effects as congruent with the consequences from fossil fuel combustion." Although we disagree that our previous text conveyed a "*false impression of novelty*", we also modified the Introduction along the lines suggested. <<

A more minor but still substantial comment: it is ignored that for wildfires in particular, a substantial part of carbon emissions is not in the form of CO2. This should be discussed. (Much of CO and CH4 emitted will end up as CO2, of course, but I think the point needs to be included).

>> 1.6 Thank you for thoroughness. This point was already mentioned in more general terms in the Methods (penultimate sentence of Section 2.1): “In all simulations, we included only the CO_2-related effects of fire and fossil fuel combustion, and not the associated aerosols and non-CO_2 greenhouse gases.”, as well as in the Section on study limitations (second paragraph of Section 4.2, starting with “Second, we neglected all non-CO_2 emissions from fire and fossil fuel.”). Neglecting non-CO_2 emissions is a common approach in studies that focus on the (relatively) long-term impacts of CO_2 emissions. Nonetheless, we added the following text to the Methods (just after the sentence cited above): “We note that fire releases some carbon as carbon monoxide (CO) and methane (CH_4); however, these species constitute less than 10% of the fire-emitted carbon (Andreae and Merlet, 2001) and get mostly oxidized to CO_2 on a timescale shorter than the one of interest here (Ehhalt et al., 2001; Boucher et al., 2009)”. <<

(2) A further major comment is that the manuscript makes the point that only fully coupled models are capable of quantifying the effects of fire emissions. There is, I believe, the danger of creating an undue monopoly for the owners of such coupled models. This runs counter to the fact, often forgotten, that the more complex models are also the ones that are more difficult to parameterise and validate. It is true that the albedo effect cannot be simulated without an atmospheric model, but whether it has to be simulated all in a single model depends on the size of the perturbation from the mean state. The temperature effects of the albedo perturbation could be estimated by a GCM and added to the temperature prescribed in an off-line terrestrial dynamic vegetation model. A further possible setup to simulate the carbon cycle effects of both emission processes is the following: force an off-line land model and some simple off-line ocean carbon cycle model (e.g. the HILDA model) with prescribed CO2 (e.g. from one of the RCPs) and burned-area scenarios, compute fire emissions, land and ocean uptake, and derive consistent fossil-fuel emissions as the residual to balance the atmospheric CO2 budget. In this setup, it would become obvious that the difference is in the process of emission, but that all CO2 molecules are equal. It is also a setup that does not require the use of coupled models. The possibility of adequate off-line approaches should be acknowledged, and the criticism of previous approaches, which were most likely used simply for convenience, emphasised much more.

>> 1.7 We agree that fully coupled climate–carbon model should not have a monopoly on climate-related studies. Although we did not actually make the point anywhere in the manuscript that only such models should be used to study fire effects, we found a few formulations that might have caused this impression and modified the text accordingly. We removed the following sentence (on p15188, starting on l3): “To date, the only study dedicated to fire in a coupled climate–carbon model with interactive vegetation dealt primarily with the consequences of major changes in future fire regime, but also found that net CO_2 emissions following changes in fire regime quickly became much smaller than gross emissions and progressively decreased over time (Landry et al., 2015).” On p15202, starting on l13: “Future studies on the differences in the carbon cycling and temperature impacts between fire and fossil fuel would nevertheless benefit from *considering*~~combining~~ the effects of non-CO_2 emissions~~ with climate–carbon feedbacks in climate models including interactive vegetation~~.” On p15202, starting on l21: “More research is therefore needed to accurately represent the highly variable and poorly quantified fate of such exchanges of pyrogenic carbon~~ in climate models~~; meanwhile, their influence on our results is speculative, but is unlikely to challenge the main outcomes we obtained.” On p15204, starting on l23: “The overarching message from the present study is that fire effects cannot be obtained from, and should not be conceived as akin to, fossil fuel emissions – rather, fire deserves its own explicit representation in ~~Earth system models~~*climate-related studies*.” The modification to the last sentence of the Abstract (please see our response 1.5) also addresses this issue.

In the last sentence of your comment, we assume you meant that the approaches of Randerson et al. (2006) and O'Halloran et al. (2012) should be criticized less (not "*more*"). In any event, following comments from the other Reviewer, we removed the two parts of the text (Introduction and Discussion) related to these studies.

Incidentally, we agree that independent land, atmospheric, and ocean models can reproduce the results we obtained, provided they exchange the adequate information on relevant perturbations frequently enough—after all, coupled climate models consist of sub-models that simply 'talk' to each other at a prescribed frequency! Using an already-coupled model or independent models with ad hoc linking is to some extent a matter of personal convenience. The issue of parameterization is a slightly different one: some fully coupled models use fewer parameters than complex stand-alone atmospheric models. Regarding the setup provided, we are not sure to fully understand the "*carbon cycle effects*" part (why "*balance the atmospheric CO2 budget*" when our objective is to quantify the fire-caused atmospheric CO_2 anomaly?), but in any event, please note that the "*temperature effects*" and "*carbon cycle effects*" parts of the assessment would need to interact together frequently, because these two effects affect each other. <<

(3) In the list of limitations, what is missing is the fact that we are dealing here with a single model only.

>> 1.8 Thank you for this suggestion. We added a fifth study limitation (that we put in fourth position in our text) to Section 4.2 (where α_L stands for the land surface albedo): "Fourth, the quantitative results we obtained were dependent upon the specific features of the UVic ESCM. For example, the simulated post-fire vegetation regrowth appeared too slow in northern grid cells (Fig. 1a), thereby overestimating the duration of both the α_L-based cooling and CO_2-based warming following fire. The carbon–concentration feedback parameters from the UVic ESCM are close to the mean from other fully coupled climate–carbon models, but its carbon–climate feedback parameters are on the high end (Arora et al., 2013), meaning that the atmospheric CO_2 levels were more affected by temperature changes than would have occurred in most other models. Once again, these factors should not challenge the main outcomes we obtained." Please see our response 1.9 for more details on vegetation regrowth. <<

(4) The recovery rates shown in Fig. 2 of Rogers et al. (2013) are about 3 times faster than those shown in Fig. 1a. This should be stated up-front instead of saying "they agree" (which they don't) and then the difference being explained. It is also not clear whether the explanation is sufficient to account for the rather large difference. What would be needed are results from a simulation that show recovery times similar to the observed ones.

>> 1.9 We appreciate once again your thoroughness; here, our response consists of four elements. First, our previous text was: "In northern forests, the succession among the different PFTs (Fig. 1a) agreed with observation-based trajectories (Rogers et al., 2013), while the impacts on biomass (Fig. 1c) and α_L (Fig. 1e) were consistent with field observations (Amiro et al., 2006; Goulden et al., 2011). The overall slower return to pre-fire conditions compared to observations came from the lasting climatic effects from the extreme 200 Pg C fire pulse (see Sect. 3.2)." So we did state that the quantitative results differed, just after noting the agreement in the succession trajectories, which we consider to be a qualitative concept. Nonetheless, we reformulated the text (please see below).

Second, the results from Rogers et al. (2013) are adequate for a qualitative assessment, but are themselves uncertain. The succession trajectories they obtained very likely included many unburned patches, because mean tree cover immediately after fire "remained above 22%" (with +1 standard error going up to ~40%; their Figure 2b), thereby leading to higher levels of tree cover. Moreover, their results involved the combination of two MODIS (satellite) datasets. The most relevant one here (MOD44B, providing percent tree cover) actually gave a stabilization of mean tree cover around ~60% for years 60–85, with no data afterwards (their Figure 2b). This differs noticeably from the final succession trajectories per plant functional type (PFT; their Figure 2c–e), which were based on MCD12Q1. This dataset provides a classification by PFT based on a 'winner-takes-all' approach; hence the entire pixel will be assigned to the needleleaf tree PFT from the time this PFT covers >50% of the pixel, thereby also leading to higher levels of tree cover. Here we are not negating that recovery simulated by TRIFFID (the dynamic vegetation module of UVic) is too slow, but the actual discrepancy is likely smaller than suggested by the quantitative results from Figure 2e of Rogers et al. (2013) and could also be affected by other factors, including the specific geographic location of the grid cell used in our Fig. 1a.

Third, the objective of the first paragraph of Section 3.1 (including Fig. 1) is to show that post-fire simulated land responses are reasonable. The outcomes of our study, which involved comparing the very different effects from fire and fossil fuel combustion over a 1000-year timescale, do not hinge upon a post-fire vegetation recovery being possibly delayed by up to several decades. An untold reason why we showed these results is the following: some people seem to believe, based on the study of Arora and Boer (2006), that TRIFFID is totally unable to simulate the coexistence of various PFTs (a senior research scientist recently tried to convince one of us this was absolutely the case!). As far as we know, there is nothing wrong with the results of Arora and Boer (2006), but the conditions for which they showed no PFT coexistence do not fully correspond to TRIFFID.

Fourth, we performed additional simulations to assess whether the explanation we provided was sufficient to account for the difference and found that it was not! Following the same fire pulse burning 88% of this grid cell only (with no fire in the other "fire cells", thus leading to a very small impact on global climate), the competition between C_3 grasses and shrubs was slightly altered, with marginal impacts on the regrowth of needleleaf trees. We performed more simulations with different pulse levels and found that this element had a greater impact. Simulated tree recovery was a little faster for a pulse burning 78% of the grid cell, which corresponds to the 22% initial tree cover of Rogers et al. (2013), and much faster for a pulse burning 50% of the grid cell.

While the previous considerations are interesting, they are much too detailed to appear in a study that does not primarily aim to quantify post-fire land dynamics, but deals instead with the major differences between fire and fossil fuel combustion effects. We therefore limited ourselves to adjusting the previous text in the light of these findings: "In northern forests, the succession among the different PFTs (Fig. 1a) was qualitatively similar to, but noticeably slower than, observation-based trajectories (Rogers et al., 2013).", deleted the previous sentence starting with "The overall slower return to pre-fire conditions [. . .]", and added the study limitation presented in our previous response (1.8). <<

The same publication as well as Almiro at et al. (2006) also show albedo for summer and winter/spring, both of which differ substantially from the values shown in Fig. 1ef). Please explain why that is and why you believe the published values support your model results. Also, the way p15193, 1st paragraph is written suggests that Amiro et al. (2006) is a source for biomass changes. I could not find such results in that publication. Please associate references more clearly, e.g. Goulden et al. (2011) show changes in biomass that are roughly consistent with Fig. (1c).

>> 1.10 Please remember that the fire-caused impact on energy exchanges is related to the change in α_L. Consequently, there is little to explain regarding the values shown in Fig. 1f, where α_L is practically unaffected (which is normal as vegetation recovery is extremely fast in savannas). Concerning Fig. 1e,

our results for the mean change in α_L are consistent with the values shown in Figures 1 (summer, day of year 177–205) and 2 (winter, DOY 1–60) of Amiro et al. (2006). The equation they provide for summer leads to a mean change of 0.050 over the first 50 years after the fire event when compared to 150-year old stands. (Their equation neglects the short-term decrease in α_L from surface blackening, which is appropriate given that we also neglected this effect in our study. Their linear regression further overestimates the initial increase in α_L because it excludes the initial 'plateau' before the values start decreasing.) For winter, their equation leads to a mean change of 0.134 over the first 50 years, compared to 150-year old stands. Our value for the mean annual $\Delta\alpha_L$ over the first 50 years is 0.054. Since annual α_L is much closer to summer than winter values in northern latitudes (because proper averaging accounts for the much higher solar radiation in summer vs. winter) and the 0.050 summer value we derived above was a little overestimated, the results agree reasonably well, especially in the context of the major variability involved (Amiro et al., 2006). The validity of the simulated $\Delta\alpha_L$ values was also supported by the following text (end of Section 3.1): "Second, the differences in α_L between the current fire regime and a no-fire world simulated by Landry et al. (2015) led to a global radiative forcing of -0.11 W/m^2 without the effect of surface blackening and -0.07 W/m^2 with surface blackening, in agreement with observation-based estimates (Ward et al., 2012) (note that we did not include surface blackening in the current study)." Finally, we reformulated the sentence to better assign references: "Simulated fire-caused changes also appeared reasonable when compared with field observations for biomass (Fig. 1c) (Goulden et al., 2011) and α_L (Fig. 1e) (Amiro et al., 2006)." <<

Minor comments:

(1) I could not find a map of the grid cells designated as fire prone. This should be provided to give the reader a better feel for the realism of the spatial distribution. It would also be good to have the distribution of burned area within 27 degrees of the equator against the remaining areas compared to the GFED4 data, in order to better judge the sensitivity study presented in Fig. 9.

>> 1.11 Thanks for this suggestion; Figure R1 (at the end of our response) will be the new Fig. 1 and we will refer to it where appropriate. About its "*realism*", please remember that the spatial distribution of "fire cells" directly reflects locations where fire occurred at least once between January 2001 and December 2012 according to GFED4. The sensitivity analysis we presented in our Fig. 9 did not aim to reproduce the quantitative distribution of burned area across grid cells from GFED4 data—it would be impossible to obtain a 100 Pg C fire pulse under such a constraint—so we do not think the comparison suggested would bring useful information. <<

(2) p 15187, l5: there should be separate citations for the emissions and for the burned area. Burned area studies cited should be from observations rather from models, and emissions at least from studies based on observed burned area. Some of the papers cited are fully prognostic models, and their estimates of burned area differ far too much from (still uncertain of course!) observations to be citable here.

>> 1.12 We modified the text as suggested and moved to another sentence the references to studies using prognostic models (in which we replaced Thonicke et al. (2010) by Arora and Boer (2005), as the former also uses LPJ). The text now reads: "Fire currently affects around 300–500 Mha yr^{-1} *(Mieville et al., 2010; Randerson et al., 2012; Giglio et al., 2013)*, leading to gross emissions *(i.e., accounting only for the combustion of vegetation and soil–litter)* of 1.5–3 Pg C yr^{-1} *(Mieville et al., 2010; van der Werf et al., 2010; Randerson et al., 2012)*~~from the direct combustion of vegetation and soil–litter (Kloster et al., 2010; Mieville et al., 2010; Thonicke et al., 2010; van der Werf et al., 2010; Randerson et al., 2012;~~

~~Giglio et al., 2013; Li et al., 2014)~~. The potential for modifications in the current fire regime to modulate climate change stimulated the explicit representation of fire in the Lund–Potsdam–Jena (LPJ) Dynamic Global Vegetation Model (DGVM; Thonicke et al., 2001), and later on into various other similar process-based models of climate–vegetation interactions *(Arora and Boer, 2005; Kloster et al., 2010; Li et al., 2014)*." <<

(3) Further down in the same paragraph, Pechony and Shindell only simulate number of fires, while fire frequency is often defined as fractional burned area.

>> 1.13 Correct. But since the same authors have previously shown their "fire count" metrics to be commensurate with burned area (Pechony and Shindell, 2009) and given that it would be very surprising for the number of fires to increase without burned area also increasing, we consider that this simplification is not misleading. <<

(4) Next paragraph mentions "climate-fire feedbacks". The studies cited before do not address feedbacks, and it is not clear which feedbacks you mean. Apart from that, see my major comment (1) and suggestions to restructure the introduction. The term "climate-fire feedbacks" could actually be dropped altogether at it is not directly addressed here.

>> 1.14 Thank you for the suggestion, we modified the sentence to: "The net effect of fire on *global* carbon cycling has however received less attention than the consequences from future ~~climate–fire feedbacks~~*changes in fire activity*." <<

(5) p15188, 1st paragraph: as explained above, a set-up with an offline terrestrial model can very well account for fire-induced CO2 fertilization if the effect is for example treated as a perturbation around a mean state. At best you could state that it would be more difficult and lack the same level of consistency, even though there are always other trade-offs like parameterisability and validity of the model.

>> 1.15 Here, we may be using the word "offline" to mean slightly different things. For us, in a strictly offline setting the terrestrial model is driven by external climate data and CO_2 levels unaffected by the terrestrial state. If atmospheric CO_2 does not change based on fire activity, no fire-induced CO_2 fertilization will occur. In any event, this specific statement was not on offline approaches in general, but on the specific studies mentioned (Ward et al., 2012; Li et al., 2014), which did not account for fire-induced CO_2 fertilization and other relevant fire-related impacts (e.g., on temperature); please see our response 1.2 for the revised version of this text. <<

(6) Same page, last sentence: I suggest that the introduction start with this sentence, include a more detailed description of the effects, then goes on with the histrocal run-down and continues to criticize previously used approaches.

>> 1.16 Thanks for this suggestion, which we brought to our revised Introduction. <<

(7) p15189, l12-16: here again the use of the word "emissions" is misleading, as what you mean is the process of emissions (i.e. fire in a combustion chamber vs. wildland fire), not the emission itself (the effect of emission could be e.g. the injection height).

>> 1.17 Please see our response 1.3 to see how we addressed this issue. <<

(8) p15194, l8: "found into the ocean", typo?

>> 1.18 We revised the text to: "taken up by the ocean". <<

(9) same page, "These two features illustrate a fundamental distinction between fossil fuel and fire: fossil fuel emissions represent a near-permanent addition of CO2 to the active (i.e., non-geological) carbon cycling pools, whereas fire pulses temporarily reshue the carbon already existing in these pools." This statement, by being rather obvious not only for specialists, rather belongs in the introduction, if it is at all needed. Here, it sounds overly pedagogical.

>> 1.19 We removed the sentence. <<

(10) p15195, l21: but note that the recovery time is longer than in the studies cited.

>> 1.20 We assume you meant line number 12, not 21? Even in this case, we fear we do not understand the comment. The studies cited (Matthews and Caldeira, 2008; Eby et al., 2009) found a pretty stable increase in global mean atmospheric surface temperature following pulses of fossil fuel CO_2 (no "*recovery time*" observed), consistent with what we obtained for our fossil fuel pulses (Fig. 3a). <<

(11) next page, l1-7: please use more objective and neutral language than "much more similar", "yet at a closer look", and "not actually equal". This sounds like a personal account of a researcher. Please leave room for a different impression created in the reader of the manuscript.

>> 1.21 We changed the text as follows: "for the atmosphere, however, the CO_2 anomalies were ~~much~~ more similar (Fig. 4a vs. Fig. 2b)*, though not identical as can be seen in Fig. 4b.* ~~Yet a closer look at the results reveals that the atmospheric anomalies were not actually equal (Fig. 4b).~~" <<

(12) same page, l8: "Based on CO2 alone" is misleading, because it sounds like as if it implies no albedo effect.

>> 1.22 This is actually what we mean: without the albedo effect, global temperature would be higher in fire than in fossil fuel simulations (because atmospheric CO_2 levels are higher in fire simulations). "Based on atmospheric CO_2 alone, one would thus expect T_s to be higher for fire than for fossil fuels, yet the opposite was in fact observed (Fig. 4c) due to the opposite impacts on α_L (Fig. 4d)." <<

(13) Same page, l19-20: Note again that fossil-fuel (burning!) emissions also come from fire, so the statement does not make sense as it is. It is also not the emission that makes the difference, but the fact that different things are combusted.

>> 1.23 We modified the sentence to: "The previous results provide relevant information regarding fundamental differences between *the effects resulting from CO$_2$ emissions created by* fire ~~and~~*vs.* fossil fuel ~~CO$_2$ emissions~~*combustion*, but were based on single pulses of fire activity." (please also see our response 1.3). <<

(14) Next page, l2-5: I am wondering who would be interested in cumulative gross emissions, or fluxes in general? I would suggest dropping these arguments, cumulative gross fluxes are more or less an oxymoron. It also contributes to the impression of over-selling the results.

>> 1.24 We appreciate your skeptical perspective, but we disagree for two reasons. First, most research on global fire-caused CO$_2$ fluxes has dealt with gross fluxes until now. Given that we still find comparisons of these fluxes with CO$_2$ emissions from fossil fuel in the literature, the distinction between gross and net emissions from fire has apparently not been fully assimilated by everyone yet. We thus want to clarify that gross emissions will keep increasing forever after a transition to a new stable fire regime, even though the much more relevant annual net emissions have been close to zero for a long time. Second, one thrust of our manuscript is to systematically compare fire with fossil fuel combustion. In this latter case, cumulative gross fluxes (since 1850 or even earlier dates) are still the matter of very active research, so some readers might wonder why we would not touch upon the equivalent for fire. <<

(15) p15198, l25: again, it is not the CO2 emitted that makes the difference.

>> 1.25 Please see our response 1.3 to this same comment. <<

(16) next page, l7: "wildland fire", not fire. The sentence is rather trivial, because a vegetation burning fire of course has a much more direct impact on land carbon than the indirect effect of CO2. We are here talking about effects at vastly different scales.

>> 1.26 We agree that the sentence presents an idea that is easily understood, but do not see what is wrong with this: explanations have to start somewhere, and progressing from what is known to new or more complex considerations is often advisable. About the use of the expression "*wildland fire*" instead of "*fire*", our entire manuscript uses the latter and we think it is preferable to avoid mixing terminology. However, we added a note in the Introduction about the other terms that are sometimes used with the same meaning as "fire" here (i.e., wildland fire, wildfire, and open vegetation burning). <<

(17) p15200: "These fundamental differences imply that fire impacts cannot be accurately estimated from simulations of fossil fuel emissions in climate models." This statement is too general and one would ask who would have the idea to do this. Rather, the manuscript should specifically criticise concrete examples of previous publication and then state that such and such approximation has been found to lead to unacceptable results.

>> 1.27 Once again, we are afraid we do not understand the comment. This sentence was the beginning of a paragraph in which we provided two such concrete examples (Randerson et al., 2006; O'Halloran et al., 2012). In any event, we removed this entire paragraph based on the comments from the other Reviewer. <<

(18) p15201: please don't use purely prognostic simulations as a source for global emissions (see above comment).

>> 1.28 We modified the text to: "Our fire regimes were therefore more severe than the current situation on Earth, as seen with our equilibrium results of $\geq$ 0.9 Gha yr^{-1} for burned area and $\geq$ 7.3 Pg C yr^{-1} for gross emissions under stable regimes (Table 3), vs. current values of 0.3–0.5 Gha yr^{-1} *(Mieville et al., 2010; Randerson et al., 2012; Giglio et al., 2013)* and 1.5–3 Pg C yr^{-1} *(Mieville et al., 2010; van der Werf et al., 2010; Randerson et al., 2012)*, respectively~~ (Kloster et al., 2010; Mieville et al., 2010; Thonicke et al., 2010; van der Werf et al., 2010; Randerson et al., 2012; Giglio et al., 2013; Li et al., 2014)~~." <<

(19) p15204, l10-11: I am not sure why I should expect anything but gross emissions to continue? Please explain what is new and unexpected here, or drop the statement.

>> 1.29 We modified the text to: "~~While~~*As expected,* non-zero gross emissions were maintained indefinitely following a stable fire regime change, *whereas* most of the net emissions actually occurred relatively quickly after the regime shift and net emissions progressively decreased to almost zero (Fig. 5)." Please also see our response 1.24 to a very similar comment. <<

Revised Introduction

Fossil fuel emissions entail a net transfer of CO_2 from geological reservoirs to the much more active atmospheric, oceanic, and terrestrial carbon pools, thereby increasing the total amount of carbon in these pools and leading to an atmospheric CO_2 anomaly that decreases only gradually on a millennial timescale (Archer et al., 2009; Eby et al., 2009; Joos et al., 2013). This atmospheric CO_2 anomaly causes global warming that remains stable over thousands of years (Matthews and Caldeira, 2008; Eby et al., 2009). The atmospheric CO_2 anomaly also gives rise to a global CO_2 fertilization effect that decreases land surface albedo, due to dynamic vegetation expansion and generally higher vegetation cover, with an additional warming resulting from this fertilization-induced albedo decrease (Matthews, 2007; Bala et al., 2013).

Fire (also referred to as wildland fire, wildfire, and open vegetation burning) is a conspicuous disturbance in most terrestrial ecosystems, with considerable impacts on vegetation and climate (Bonan, 2008; Running, 2008; Bowman et al., 2009). Contrary to fossil fuel combustion, fire does not entail a net addition of CO_2 to the three active carbon pools of the Earth System, but simply redistributes the carbon already existing within these global pools. Except when used for permanent land clearing, fire usually triggers a strong local-scale vegetation regrowth response lasting years to decades depending upon the ecosystem (van der Werf et al., 2003; Goulden et al., 2011); hence the resulting atmospheric CO_2 anomaly and the concurrent global CO_2 fertilization are of shorter duration than after fossil fuel combustion. Fire also causes major modifications to land–atmosphere exchanges of energy through altered surface albedo and sensible/latent heat partitioning (Bremer and Ham, 1999; Amiro et al., 2006). Besides a short-term decrease due to surface blackening, local albedo generally increases after a fire event, thereby leading to a regional-scale cooling that is consequential at the global scale (Ward et al., 2012; Landry et al., 2015). For a given amount of emitted CO_2, fire therefore differs from fossil fuel combustion in terms of: 1) average lifetime of CO_2 molecules in the atmosphere; and 2) non-CO_2 climatic impacts. When comparing fire with fossil fuel combustion, the expression "CO_2 emissions" will henceforth implicitly include the consequences from these differences in atmospheric lifetime and surface albedo.

Fire currently affects around 300–500 Mha yr^{-1} (Mieville et al., 2010; Randerson et al., 2012; Giglio et al., 2013), leading to gross emissions (i.e., accounting only for the combustion of vegetation and soil–litter) of 1.5–3 Pg C yr^{-1} (Mieville et al., 2010; van der Werf et al., 2010; Randerson et al., 2012). The potential for modifications in the current fire regime to modulate climate change stimulated the explicit representation of fire in the Lund–Potsdam–Jena (LPJ) Dynamic Global Vegetation Model (DGVM; Thonicke et al., 2001), and later on into various other similar process-based models of climate–vegetation interactions (Arora and Boer, 2005; Kloster et al., 2010; Li et al., 2014). These efforts have paved the way to studies that projected an increase in fire frequency and gross CO_2 emissions over the 21st century (Scholze et al., 2006; Pechony and Shindell, 2010; Kloster et al., 2012). The net effect of fire on global carbon cycling has however received less attention than the consequences from future changes in fire activity. In their seminal study, Seiler and Crutzen (1980) concluded that net biospheric emissions, coming mostly from fire, could range between ± 2 Pg C yr^{-1} by adding the effects of vegetation regrowth and other processes to their estimate of 2–4 Pg C yr^{-1} for gross fire emissions. The net effect of fire on global terrestrial carbon storage has then apparently been left unaddressed for more than three decades, until Ward et al. (2012) suggested a fire-caused net reduction of ~ 500 Pg C in pre-industrial land carbon. They also found that this reduction could currently be slightly lower (around 425 Pg C) due to offsetting effects between fire and land-use and land cover changes (LULCC), but could increase to about 550–650 Pg C by the end of this century due to a climate-driven increase in fire activity. More recently, Li et al. (2014) concluded that net fire emissions were equal to 1.0 Pg C yr^{-1} on average during the 20th century, compared to gross emissions of 1.9 Pg C yr^{-1} on average over the same period. While the fact that vegetation regrowth offsets a fraction of gross fire emissions has been appreciated for some time, previous global quantifications of the difference between gross and net emissions have been performed with first-order estimates (Seiler and Crutzen, 1980) or in offline terrestrial models (Ward et al., 2012; Li et al., 2014), and have neglected relevant processes. Indeed, net fire CO_2 emissions differ from gross emissions because they include not only the gradual decomposition of the non-trivial fraction of vegetation killed by fire but not combusted (especially for trees) and the post-fire vegetation regrowth, but also the effects of various feedbacks like the fire-induced CO_2 fertilization of terrestrial vegetation, or the impacts on vegetation productivity and soil–litter decomposition of temperature changes caused by modified atmospheric CO_2 and surface albedo.

In this study, we used a coupled climate–carbon model with interactive vegetation to advance the current knowledge regarding the effects of fire CO_2 emissions on the global carbon cycle and temperature. Using such a model allowed us to account for the various feedbacks mentioned previously (i.e., CO_2 fertilization and temperature–CO_2 interactions), as well as the major role of the ocean in the fate of the fire-emitted CO_2. We focussed on non-deforestation fires that allow the different vegetation types to compete and grow back in the recently burned area, because they constitute the bulk of global burned area and gross emissions (van der Werf et al., 2010) and have been much less represented in climate models than the LULCC events associated with deforestation fires. Our main objective is to compare the long-term effects of fire CO_2 emissions to corresponding levels of fossil fuel CO_2 emissions, for single fire pulses and stable fire regimes. A second objective is to quantify the differences between gross and net fire CO_2 emissions over 1000 years following major changes in fire frequency. To facilitate the interpretation of results, we performed all simulations against a background climate corresponding to pre-industrial conditions.

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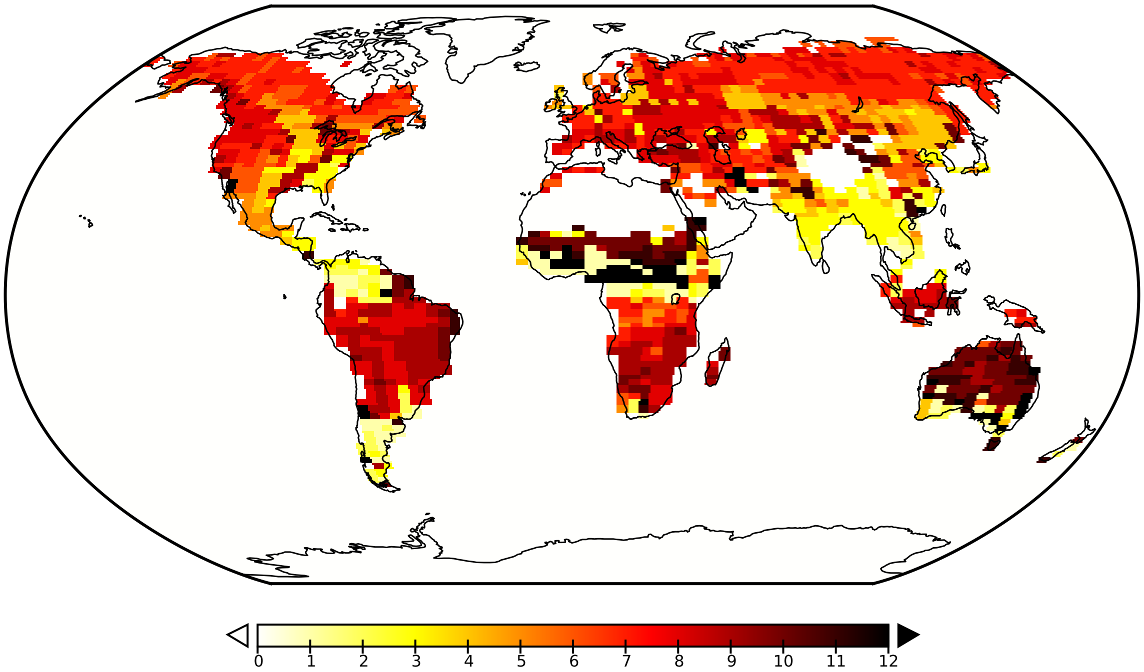

Figure R1. "Fire cells" used in the fire simulations. Numbers from 1 to 12 give the month of the year when fire occurs, whereas number 0 corresponds to grid cells without fire.

Review #2: please note that the review of our manuscript is in italics, with our responses given in a regular font.

The manuscript by Landry and Matthews documents how CO2 emissions generated from global wildfires differ from those generated by fossil fuel combustion in terms of atmospheric fraction and temperature. The authors use a coupled model to assess this, and also show temperature effects from altered land surface albedo. There are some potentially interesting and useful results, including the net vs. gross fire emissions after sustained changes in fire frequency, some of the climate feedbacks, and additions to the literature on atmospheric fraction and impulse response functions. However, I find much of the study design and the paper's presentation to be ill-conceived, and therefore cannot recommend publication in its present form. My major criticisms are below.

>> 2.1 We thank you for your time and thoughtful comments that resulted in a substantial improvement of our manuscript; please see our responses below for more details. At the onset, we would like to note that the part of the "*study design*" you considered "*ill-conceived*" was not related to our central results, but to one implication of these results that we presented in a single paragraph of the Discussion. As we explain below, we have now removed this paragraph from the manuscript, and have also included clarifications in several places in the revised text. <<

Major comments:

(1) Much of the language throughout focuses on the fact that gross fire emissions are not equal to net because of ecosystem regrowth, and that somehow this concept is novel and not accounted for in past studies. I find this off-base. Studies that attempt to calculate the effect of changing fire regimes on carbon stocks or fluxes obviously need to account for regrowth. Differences in carbon stocks and hence net transfers to the atmosphere will of course only be realized if mean fire frequencies or ecosystem characteristics (vegetation type, etc.) change in a way that affect mean standing carbon stocks. This is not a new concept, and has been extensively published on.

>> 2.2 We are grateful for this comment, because it shows we were not clear enough on the difference between net and gross emissions. We agree that the role of post-fire regrowth is well recognized and that many stand- to regional-level studies have accounted for this CO_2 flux in various ecosystems. In the literature on the global-scale effects of fire, the regrowth flux has not been considered as frequently (most studies focussing on combustion-only gross emissions), but we presented in the Introduction three studies that did account for it in their estimate of net emissions (Seiler and Crutzen, 1980; Ward et al., 2012; Li et al., 2014). The difference between net and gross emissions also includes the decomposition of the vegetation that is killed by fire, but not combusted; this flux is important soon after a fire event, and explains why net emissions can initially reach higher values than gross emissions (e.g., Fig. 5, particularly visible in panels a and b). The three previous global-scale studies accounted for this process, but neglected several additional factors. First, fire-emitted CO_2 fertilizes the terrestrial vegetation at the global scale, thereby reducing the net land-to-atmosphere fire-caused CO_2 emissions (please remember that net emissions are defined as the difference in total land carbon storage between a control and a fire simulation). This effect has been shown to be meaningful for fire scenarios more realistic than the ones considered here (Landry et al., 2015). Second, the higher atmospheric CO_2 due to fire warms the climate globally, which can affect vegetation productivity and soil–litter decomposition, modulating once again the net emissions. Third, the post-fire local change in land surface albedo (α_L) has overall the opposite effect, because on average it cools the climate. Other feedbacks are possible (e.g., the fire-caused change

in temperature affects ocean CO_2 solubility, which modifies atmospheric CO_2 levels and thus the CO_2 fertilization effect), but these are probably second- or third-order effects in the context of our study.

We have included the following clarifications in the Introduction (which we extensively revised to address various comments, the revised version appearing at the end of our response) "~~The latter two studies were however performed~~ *While the fact that vegetation regrowth offsets a fraction of gross fire emissions has been appreciated for some time, previous global quantifications of the difference between gross and net emissions have been performed with first-order estimates (Seiler and Crutzen, 1980) or* in offline terrestrial models *(Ward et al., 2012; Li et al., 2014)*~~, and were therefore unable to account for various climate fire feedbacks, including fire-induced CO_2 fertilization and the impact of changes in surface albedo on temperature~~ *and have neglected relevant processes. Indeed, net fire CO_2 emissions differ from gross emissions because they include not only the gradual decomposition of the non-trivial fraction of vegetation killed by fire but not combusted (especially for trees) and the post-fire vegetation regrowth, but also the effects of various feedbacks like the fire-induced CO_2 fertilization of terrestrial vegetation, or the impacts on vegetation productivity and soil–litter decomposition of temperature changes caused by modified atmospheric CO_2 and surface albedo.*" <<

(2) The authors derive separate impulse response functions (IRFs) from global wildfires and from fossil fuel emissions. The premise is that studies that use the latter to inform on fire impacts are misguided (e.g. Randerson et al. 2006, O'Halloran et al. 2012). But there are fundamental differences in the way past studies and this one are conceptualized. The referenced prior work attempted to understand the long-term legacy of fire CO2 emissions in the atmosphere from one particular local fire event. In that case they accounted for both local ecosystem regrowth and other global land and carbon sinks as derived from fossil fuel CO2 pulses. In essence this isolates the effect of one model 'pixel' or 'grid cell', and assumes the rest of the world remains unchanged, i.e. a partial derivative. This, to me, mostly makes sense given the multitude of drivers for other future land and ocean carbon sinks. The present manuscript, however, derives its fire IRFs from simulations where nearly every grid cell burns (ones that had some level of fire activity in the MODIS era) and is allowed to regrow. This IRF then is only applicable in the case of a drastic global wildfire event. If we are scientifically concerned with changes to local to regional regimes (as is the case generally and in the two aforementioned studies), the former approach seems appropriate. If, for some reason, we were attempting to understand the fate of CO2 in the atmosphere in the context of most of the land surface burning at once and being allowed to regrow, then we would use the fire IRFs derived here. That situation, however, does not seem relevant to most current research questions and issues. If I am misinterpreting their analysis of fire IRFs, then I apologize, but in that case the authors need to be more clear on exactly what their fire IRFs should and should not be used for. I have a serious concern that if published as is, the fire IRFs would be misinterpreted and used in contexts that are not applicable.

>> 2.3 Thank you for this comment and another closely related one below (*[15200, line 25]*); for convenience, we respond to both comments here. First, although we performed an additional analysis consisting of a much smaller fire pulse occurring in a single grid cell and still consider that our conclusion (i.e., the approaches of Randerson et al. (2006) and O'Halloran et al. (2012)—which used IRFs derived from previous simulations of fossil fuel CO_2 emissions to estimate the fire-caused atmospheric CO_2 anomaly—do not work as intended) is valid, we ended up removing this part of the text because we now realize that such an analysis deserves a dedicated study. We want to underline that this analysis was not a main part of our study, but a single paragraph we added to Section 4.1 (Discussion) for illustration purposes. As stated in the Introduction: "Our main objective is to compare the long-term effects of fire CO_2 emissions to corresponding levels of fossil fuel CO_2 emissions, for single fire pulses and stable fire

regimes. A second objective is to quantify the differences between gross and net fire CO_2 emissions over 1000 years following major changes in fire frequency."

Second, we agree that the fire IRFs we presented before could have been misused. In particular, simply replacing fossil fuel-based IRFs with our fire-based IRFs in the convolution approach (i.e., the one used by O'Halloran et al. (2012), which to our knowledge is the most common way to estimate the fate of the atmospheric CO_2 anomaly caused by fire and other terrestrial changes) does not work either, as we validated with our own results. The fire IRFs we presented in our former Table 2 excluded the first couple of years from the fit, as we mentioned in the original text, because the fire-caused atmospheric CO_2 anomaly increased for a few years (due to decomposition of the fire-killed vegetation) before gradually decreasing. Moreover, the maximum value of the fractional atmospheric anomaly was higher than 1.0 (because the size of the fire pulse was defined based on gross, not net, emissions). Over the first couple of years, there was consequently a major discrepancy between actual fire results and the corresponding fire IRF. This discrepancy is irrelevant for the long-term behaviour we want to illustrate, but is consequential in the context of the convolution framework where the same IRF is applied over and over to all yearly land–atmosphere CO_2 fluxes. Moreover, to be fruitfully applied to specific fire events, fire IRFs should probably be derived from regional instead of global pulses in order to reflect the spatial variations of fire-related impacts (e.g., northern forests vs. savanna, Fig. 1), in line with the spirit of your comments. Since Fig. 2c illustrates clearly enough the difference we want to highlight regarding the long-term behaviour of fire vs. fossil fuel, we decided to remove IRFs from the manuscript.

Consequently, the major revisions we brought consisted of removing: 1) the paragraph of Section 4.1, along with Fig. 3, where we analyzed the approaches of Randerson et al. (2006) and O'Halloran et al. (2012); 2) Table 2, in order to prevent a possible misuse of the fire IRFs we derived; 3) the part of the Introduction that presented IRFs and various studies, including Randerson et al. (2006) and O'Halloran et al. (2012), that used fossil fuel-derived IRFs to quantify the atmospheric CO_2 anomaly caused by fire or other terrestrial changes (p15188, from l8 to l25); and 4) the text referring to IRFs in the Results (p15195, from l1 to l8).

(3) I generally found the justification for using a coupled model to address these issues lacking. I do not think the tool is inappropriate, but the authors seem to push the idea that only a coupled model can be used to answer these questions. To me, the benefits of using a coupled modeling approach are (i) that it can account for the CO2-climate feedbacks generated by changing fire regimes and (ii) that it can estimate the temperature response from CO2 and other forcing agents such as albedo and aerosols. In the case of (i), the authors do not actually simulate the effects of CO2 or climate on fire regimes; these are prescribed. Climate and CO2 do affect land carbon cycling in general, but the results have limited implications because the model simulations are highly theoretical (or experimental) and cannot easily be tied to actual future projections. In the case of (ii), the authors do discuss the impacts of land surface albedo on temperature. However, they do not include char, which can be one of the dominant albedo effects in many terrestrial systems such as grasslands and savannas (see Figure B1 in Ward et al. 2012). So the fire-albedo affects are incomplete. Moreover, the authors do not account for other non-CO2 gases or, more importantly, fire aerosols, which are likely the dominant impact of fires on climate. To be clear, I'm not arguing that the authors need to include these effects in this manuscript. But I am arguing that the major benefits of using a coupled model are not really being taken advantage of. I only stress this because much of the language seems to imply that a coupled model must be used to assess these issues. As W. Knorr pointed out, this is not true.

>> 2.4 First, we agree that coupled climate models are not the only tools suitable to compare the climatic impacts of fire vs. fossil fuel combustion, and did not make such a claim in the manuscript.

However, we strove to identify the formulations that might have caused this impression and modified the text accordingly. The last sentence of the Abstract: "Overall, our study calls for the explicit representation of fire *activity*~~in climate models, rather than resorting to ersatz results coming from fossil fuel simulations,~~ as a valuable step to foster a more accurate understanding of its impacts ~~in the Earth system~~*on global carbon cycling and temperature, compared to conceiving fire effects as congruent with the consequences from fossil fuel combustion*." We removed the following sentence (on p15188, starting on l3): "To date, the only study dedicated to fire in a coupled climate–carbon model with interactive vegetation dealt primarily with the consequences of major changes in future fire regime, but also found that net CO_2 emissions following changes in fire regime quickly became much smaller than gross emissions and progressively decreased over time (Landry et al., 2015)." On p15202, starting on l13: "Future studies on the differences in the carbon cycling and temperature impacts between fire and fossil fuel would nevertheless benefit from *considering*~~combining~~ the effects of non-CO_2 emissions~~ with climate–carbon feedbacks in climate models including interactive vegetation~~." On p15202, starting on l21: "More research is therefore needed to accurately represent the highly variable and poorly quantified fate of such exchanges of pyrogenic carbon~~ in climate models~~; meanwhile, their influence on our results is speculative, but is unlikely to challenge the main outcomes we obtained." On p15204, starting on l23: "The overarching message from the present study is that fire effects cannot be obtained from, and should not be conceived as akin to, fossil fuel emissions – rather, fire deserves its own explicit representation in ~~Earth system models~~*climate-related studies*."

Second, we clearly stated in the Methods and Discussion that we did not consider the effects of non-CO_2 emissions (including the impact of char on α_L, which would not occur if combustion led to 100% CO_2 emissions). Such an effective 'decoupling' of CO_2 from concurrent emissions of gases and aerosols is common in studies assessing the long-term fate of emitted CO_2 (Eby et al., 2009; Joos et al., 2013). We consider highly unlikely that accounting for non-CO_2 emissions would alter our main conclusions on the major differences between fire and fossil fuel, or on the differences between net and gross fire emissions.

Third, the reason we used a coupled climate model with interactive vegetation is partly related to the benefit "*(i)*" you mentioned. Although we did not study feedbacks between climate and fire occurrence, CO_2–climate feedbacks played a relevant role in our study, as explained in our response 2.2 (i.e., fire- vs. fossil fuel-induced CO_2 fertilization, and the impacts of fire- vs. fossil fuel-induced temperature changes on CO_2 exchanges). Using a coupled model ensured to capture these effects, which arguably ends up being easier than having to 'manually' adjust fluxes among independent models to account for them—and is probably why, to our knowledge, all previous studies deriving IRFs for fossil fuel used coupled climate models of varying complexity. Another reason we used such a model is that we were interested in the responses of the three major carbon pools, including the ocean which plays a major role in the CO_2 exchanges following emissions from fire or fossil fuel (please see Figs. 2 and 6). To clarify this point, we added the following sentence to the Introduction, just after stating that we use a coupled climate model for the study: "Using such a model allowed us to account for the various feedbacks mentioned previously (i.e., CO_2 fertilization and temperature–CO_2 interactions), as well as the major role of the ocean in the fate of the fire-emitted CO_2." <<

Minor comments: -[15188, line 23] This is the type of language that I find ill-conceived. Studies such as O'Halloran et al. 2012 account for local ecosystem regrowth from a local fire event, which is essentially 'the fundamental' difference between fire and fossil fuel emissions the authors mention. Past studies such as this are generally not interested in the fate of atmospheric CO2 when the entire biosphere is regrowing from one large pulse fire event.

>> 2.5 Please see our response 2.2 for the clarifications we brought to the text regarding other processes besides vegetation regrowth that play a major role in the differences between fire and fossil fuel emissions. Also note that this part of the Introduction has been entirely modified. <<

-[15191, line 13] Parentheses should not be put around complete sentences

>> 2.6 We removed the parentheses that previously enclosed the sentence. <<

-[Figure 1] Qualitatively, the PFT and albedo succession curves match the mentioned observation-based estimates. But quantitatively they do not. The presented annual (?) albedo anomaly is considerably smaller for what's published in the North American boreal in winter/spring, but larger than what's published in summer (e.g. figures from Amiro et al. 2006). Hence it is difficult to compare. And the PFT regrowth takes much longer in the presented model (e.g. shrub PFTs generally last 20-30 years in Alaska and Canada as shown in Rogers et al. 2013, but last up to 300 years here). These differences should at least be mentioned.

>> 2.7 Thank you for this comment. The goal of Fig. 1 was indeed to show that results agree qualitatively with observation-based estimates and have a reasonable magnitude. We clarified the text, stating more explicitly the quantitative disagreement with the results from Rogers et al. (2013): "In northern forests, the succession among the different PFTs (Fig. 1a) *was qualitatively similar to, but noticeably slower than,*~~agreed with~~ observation-based trajectories (Rogers et al., 2013)~~, while the impacts on biomass (Fig. 1c) and α_L (Fig. 1e) were consistent with field observations (Amiro et al., 2006; Goulden et al., 2011)~~. *Simulated fire-caused changes also appeared reasonable when compared with field observations for biomass (Fig. 1c) (Goulden et al., 2011) and α_L (Fig. 1e) (Amiro et al., 2006).*" Correspondingly, we added the following text to the Section on study limitations: "Fourth, the quantitative results we obtained were dependent upon the specific features of the UVic ESCM. For example, the simulated post-fire vegetation regrowth appeared too slow in northern grid cells (Fig. 1a), thereby overestimating the duration of both the α_L-based cooling and CO_2-based warming following fire. The carbon–concentration feedback parameters from the UVic ESCM are close to the mean from other fully coupled climate–carbon models, but its carbon–climate feedback parameters are on the high end (Arora et al., 2013), meaning that the atmospheric CO_2 levels were more affected by temperature changes than would have occurred in most other models. Once again, these factors should not challenge the main outcomes we obtained."

Incidentally, we would like to note that the results from Rogers et al. (2013), which were not based on field data but on satellite measurements, are themselves uncertain. The succession trajectories they obtained very likely included many unburned patches, because mean tree cover immediately after fire "remained above 22%" (with +1 standard error going up to ∼40%; their Figure 2b), thereby leading to higher levels of tree cover. Moreover, their results involved the combination of two MODIS datasets. The most relevant one here (MOD44B, providing percent tree cover) actually gave a stabilization of mean tree cover around ∼60% for years 60–85, with no data afterwards (their Figure 2b). This differs noticeably from the final succession trajectories per plant functional type (PFT; their Figure 2c–e), which were based on MCD12Q1. This dataset provides a classification by PFT based on a 'winner-takes-all' approach; hence the entire pixel will be assigned to the needleleaf tree PFT from the time this PFT covers >50% of the pixel, thereby also leading to higher levels of tree cover.

Regarding α_L, spatially-explicit results from the UVic ESCM are very demanding in terms of storage space (about 30 MB for each 'picture'). This is why we saved the mean value of each spatially-explicit variable once every 50 years only; saving seasonal values of α_L on a yearly basis would be far too demanding. So the changes in annual α_{L} we obtained were indeed smaller than wintertime changes, but larger than summertime changes. A quick analysis shows that our results agree reasonably well with the values from Figures 1 and 2 of Amiro et al. (2006), which show considerable variability. The equation they provide for summer changes leads to a mean change of 0.050 over the first 50 years after the fire event when compared to 150-year old stands. (Their equation neglects the short-term decrease in α_{L} from surface blackening, which is appropriate given that we also neglected this effect in our study. Their linear regression further overestimates the initial increase in α_{L} because it excludes the initial 'plateau' before the values start decreasing.) For winter, their equation leads to a mean change of 0.134 over the first 50 years, compared to 150-year old stands. Our value for the mean annual $\Delta\alpha_{\mathrm{L}}$ over the first 50 years is 0.054. Since annual α_{L} is much closer to summer than winter values in northern latitudes (because proper averaging accounts for the much higher solar radiation in summer vs. winter) and the 0.050 summer value we derived above was a little overestimated, the results agree reasonably well. The validity of the simulated $\Delta\alpha_{\mathrm{L}}$ values was also supported by the following text (end of Section 3.1): "Second, the differences in α_{L} between the current fire regime and a no-fire world simulated by Landry et al. (2015) led to a global radiative forcing of -0.11 W/m^2 without the effect of surface blackening and -0.07 W/m^2 with surface blackening, in agreement with observation-based estimates (Ward et al., 2012) (note that we did not include surface blackening in the current study)." <<

-[15193, line 11] Regarding above, the authors mention that lasting climate feedbacks are responsible for the overall slow regrowth in the model. To me this is interesting from the standpoint of a modeling exercise, but has limited application to reality. Vegetation will not be regrowing amidst immediate climate changes from a global conflagration. This is an instance where it would have been seemingly much better to run the model offline instead of in a coupled configuration.

>> 2.8 Please note that the purpose of Fig. 1 was not to provide a precise assessment of the performance of TRIFFID (the dynamic vegetation module within the UVic ESCM), but to give a flavour of simulated fire effects and their realism; a detailed quantitative assessment would likely require a dedicated study. But there was another reason why we showed these results: some people seem to believe, based on the study of Arora and Boer (2006), that TRIFFID is totally unable to simulate the coexistence of various PFTs (a senior research scientist recently tried to convince one of us this was absolutely the case!). As far as we know, there is nothing wrong with the results of Arora and Boer (2006), but the conditions for which they showed no PFT coexistence do not fully correspond to TRIFFID. We performed additional simulations to assess whether the explanation we provided (i.e., lasting climatic effects) was sufficient to account for the difference and found that it was not! Following the same fire pulse burning 88% of this grid cell only (with no fire in the other "fire cells", thus leading to a very small impact on global climate), the competition between C$_3$ grasses and shrubs was slightly altered, with marginal impacts on the regrowth of needleleaf trees. We performed more simulations with different pulse levels and found this element to have a greater impact. Simulated tree recovery was a little faster for a pulse burning 78% of the grid cell, which corresponds to the 22% initial tree cover of Rogers et al. (2013), and much faster for a pulse burning 50% of the grid cell. Consequently, we deleted the previously proposed explanation and, as mentioned in our response 2.7, acknowledged more explicitly this limitation in the Results and added a paragraph on this issue in the Discussion. <<

-[15195, line 27] "Now, what if fossil fuel emissions were instead set equal to the net land-to-atmosphere emissions from fire?" What is the rationale for this experiment? What are the implications, either practical or theoretical? Some of this comes off like an entertaining modeling exercise with limited applicability.

>> 2.9 We thank you for this question, which has led us to better explain the relevance of this set of simulations. Please remember that the main objective of our study is to "compare the long-term effects of fire CO_2 emissions to corresponding levels of fossil fuel CO_2 emissions, for single fire pulses and stable fire regimes." Now, what are "corresponding" levels? A first natural answer is for fossil fuel emissions to be equal to gross fire emissions (i.e., based on combustion only). However, a fossil fuel pulse increases the sum of carbon in the atmosphere, ocean, and land, but a fire pulse does not; it is therefore mathematically impossible for fossil fuel and fire to have the same effect on the three pools. Some readers might therefore feel that our first set of results were 'unfair' about the possibility of fossil fuel combustion having the same effect as fire. This is why we then present the second possible natural answer: let's simulate fossil fuel emissions that are equal to the net emissions from fire, year after year (this means that fossil fuel emissions become negative after a few years, as if atmospheric CO_2 was sequestered back into geological reservoirs). This represents a much more stringent test of the idea we put forward, thereby substantially strengthening our conclusion. We adjusted the text as follows: "Now, what if fossil fuel emissions were instead set equal to the net land-to-atmosphere emissions from fire *year after year over the entire simulation, a situation where we expect fossil fuel emissions to better mimick the effects from fire emissions*?" <<

-[15197, line 4] Again, who is making the argument that yearly gross emissions should be used to assess the impact of fires on the land carbon sink? To me this is not a problem in the literature or the field in general.

>> 2.10 Please note that the "cumulative impacts of fire regime shifts" we address in this Section on stable fire regimes go beyond the land carbon pool, and include the effects on the atmosphere and ocean carbon pools, as well as on the global temperature (Figs. 6 and 7). While we are unaware of people stating that gross fire emissions "*should be used*" to assess the impacts of fire on global carbon cycling and temperature, there seems to be a problem in the literature regarding the side-by-side comparisons of gross fire emissions to fossil fuel emissions (implying, implicitly at least, that they have similar effects), with no caveat regarding the difference between net and gross fire emissions. We have identified a dozen studies presenting such side-by-side comparisons over the last ten years, with five of them published since 2011. Even if many of these authors certainly understand that gross and net fire emissions differ, they end up implicitly promoting the idea that gross fire emissions are adequate to characterize climatic impacts—an idea that might very well confuse readers who do not have enough previous knowledge on these questions. <<

-[15200, line 25] I may be confused here, in which case I welcome corrections from the authors, but I do not believe this setup mimics Randerson et al. 2006. The Randerson study accounted for a single fire event's impact on atmospheric CO2 by including local ecosystem regrowth and other global land and ocean sinks. The approach mentioned here seems to account for GLOBAL ecosystem regrowth from a global conflagration, coupled with the ocean CO2 sink from a simulation in which the land had not burned. It is not surprising that this IRF does not match the actual fire IRF where the atmosphere-ocean flux was affected by the regrowing land. But this is also not a simulation that, as far as I can tell, has any obvious application; nor does it replicate past work. The same critique applies to the following attempt at mimicking what O'Halloran et al. 2012 did. To me, again, the fundamental difference is that the past work mentioned considered local post-fire regrowth while this study considers global post-fire regrowth. I do not understand where the latter scenario is applicable.

>> 2.11 Please see our response 2.3, where we responded to both comments. <<

-[15202, line 2] I assume this is some sort of typo, in that the authors mean that including char albedo would reduce the albedo cooling effect, and that including other non-CO2 emissions (CH4, effects on O3, etc) would result in additional warming?

>> 2.12 You assumed correctly. We modified the text as follows: "Accounting for *the short-term post-fire surface blackening caused by char*~~fire non-CO_2 emissions~~ would reduce the albedo cooling effect~~, due to the short-term post-fire surface blackening caused by char~~." <<

-In the figures with multiple lines and colors, consider making the fossil fuel scenarios more similar to each other and the fire scenarios more similar to each other (e.g. dashes, or similar colors). This would make reading the graphs considerably easier.

>> 2.13 Thanks for this suggestion. We distinguished fire from fossil fuel results in Figs 3a, 3b, 4b, 4c, 4d, 7a, 7b, and 7c, by using dashes for fossil fuel. <<

Revised Introduction

Fossil fuel emissions entail a net transfer of CO_2 from geological reservoirs to the much more active atmospheric, oceanic, and terrestrial carbon pools, thereby increasing the total amount of carbon in these pools and leading to an atmospheric CO_2 anomaly that decreases only gradually on a millennial timescale (Archer et al., 2009; Eby et al., 2009; Joos et al., 2013). This atmospheric CO_2 anomaly causes global warming that remains stable over thousands of years (Matthews and Caldeira, 2008; Eby et al., 2009). The atmospheric CO_2 anomaly also gives rise to a global CO_2 fertilization effect that decreases land surface albedo, due to dynamic vegetation expansion and generally higher vegetation cover, with an additional warming resulting from this fertilization-induced albedo decrease (Matthews, 2007; Bala et al., 2013).

Fire (also referred to as wildland fire, wildfire, and open vegetation burning) is a conspicuous disturbance in most terrestrial ecosystems, with considerable impacts on vegetation and climate (Bonan, 2008; Running, 2008; Bowman et al., 2009). Contrary to fossil fuel combustion, fire does not entail a net addition of CO_2 to the three active carbon pools of the Earth System, but simply redistributes the carbon already existing within these global pools. Except when used for permanent land clearing, fire usually triggers a strong local-scale vegetation regrowth response lasting years to decades depending upon the ecosystem (van der Werf et al., 2003; Goulden et al., 2011); hence the resulting atmospheric CO_2 anomaly and the concurrent global CO_2 fertilization are of shorter duration than after fossil fuel combustion. Fire also causes major modifications to land–atmosphere exchanges of energy through altered surface albedo and sensible/latent heat partitioning (Bremer and Ham, 1999; Amiro et al., 2006). Besides a short-term decrease due to surface blackening, local albedo generally increases after a fire event, thereby leading to a regional-scale cooling that is consequential at the global scale (Ward et al., 2012; Landry et al., 2015). For a given amount of emitted CO_2, fire therefore differs from fossil fuel combustion in terms of: 1) average lifetime of CO_2 molecules in the atmosphere; and 2) non-CO_2 climatic impacts. When comparing fire with fossil fuel combustion, the expression "CO_2 emissions" will henceforth implicitly include the consequences from these differences in atmospheric lifetime and surface albedo.

Fire currently affects around 300–500 Mha yr^{-1} (Mieville et al., 2010; Randerson et al., 2012; Giglio et al., 2013), leading to gross emissions (i.e., accounting only for the combustion of vegetation and soil–litter) of 1.5–3 Pg C yr^{-1} (Mieville et al., 2010; van der Werf et al., 2010; Randerson et al., 2012). The potential for modifications in the current fire regime to modulate climate change stimulated the explicit representation of fire in the Lund–Potsdam–Jena (LPJ) Dynamic Global Vegetation Model (DGVM; Thonicke et al., 2001), and later on into various other similar process-based models of climate–vegetation interactions (Arora and Boer, 2005; Kloster et al., 2010; Li et al., 2014). These efforts have paved the way to studies that projected an increase in fire frequency and gross CO_2 emissions over the 21st century (Scholze et al., 2006; Pechony and Shindell, 2010; Kloster et al., 2012). The net effect of fire on global carbon cycling has however received less attention than the consequences from future changes in fire activity. In their seminal study, Seiler and Crutzen (1980) concluded that net biospheric emissions, coming mostly from fire, could range between ± 2 Pg C yr^{-1} by adding the effects of vegetation regrowth and other processes to their estimate of 2–4 Pg C yr^{-1} for gross fire emissions. The net effect of fire on global terrestrial carbon storage has then apparently been left unaddressed for more than three decades, until Ward et al. (2012) suggested a fire-caused net reduction of ~ 500 Pg C in pre-industrial land carbon. They also found that this reduction could currently be slightly lower (around 425 Pg C) due to offsetting effects between fire and land-use and land cover changes (LULCC), but could increase to about 550–650 Pg C by the end of this century due to a climate-driven increase in fire activity. More recently, Li et al. (2014) concluded that net fire emissions were equal to 1.0 Pg C yr^{-1} on average during the 20th century, compared to gross emissions of 1.9 Pg C yr^{-1} on average over the same period. While the fact that vegetation regrowth offsets a fraction of gross fire emissions has been appreciated for some time, previous global quantifications of the difference between gross and net emissions have been performed with first-order estimates (Seiler and Crutzen, 1980) or in offline terrestrial models (Ward et al., 2012; Li et al., 2014), and have neglected relevant processes. Indeed, net fire CO_2 emissions differ from gross emissions because they include not only the gradual decomposition of the non-trivial fraction of vegetation killed by fire but not combusted (especially for trees) and the post-fire vegetation regrowth, but also the effects of various feedbacks like the fire-induced CO_2 fertilization of terrestrial vegetation, or the impacts on vegetation productivity and soil–litter decomposition of temperature changes caused by modified atmospheric CO_2 and surface albedo.

In this study, we used a coupled climate–carbon model with interactive vegetation to advance the current knowledge regarding the effects of fire CO_2 emissions on the global carbon cycle and temperature. Using such a model allowed us to account for the various feedbacks mentioned previously (i.e., CO_2 fertilization and temperature–CO_2 interactions), as well as the major role of the ocean in the fate of the fire-emitted CO_2. We focussed on non-deforestation fires that allow the different vegetation types to compete and grow back in the recently burned area, because they constitute the bulk of global burned area and gross emissions (van der Werf et al., 2010) and have been much less represented in climate models than the LULCC events associated with deforestation fires. Our main objective is to compare the long-term effects of fire CO_2 emissions to corresponding levels of fossil fuel CO_2 emissions, for single fire pulses and stable fire regimes. A second objective is to quantify the differences between gross and net fire CO_2 emissions over 1000 years following major changes in fire frequency. To facilitate the interpretation of results, we performed all simulations against a background climate corresponding to pre-industrial conditions.

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Fire vs. fossil fuel combustion: ~~all~~ the source of CO_2 emissions ~~are not created equal~~affects the global carbon cycle and climate responses

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Abstract

Fire is arguably the most influential natural disturbance in terrestrial ecosystems, thereby playing a major role in carbon exchanges and affecting many climatic processes. ~~Nevertheless, fire has not been the subject of dedicated studies in coupled climate–carbon models with interactive vegetation until very recently. Hence, previous studies resorted to results from simulations of fossil fuel emissions to estimate the effects of fire-induced emissions. While atmospheric~~ While in the atmosphere, fire-emitted CO_2 has the same radiative effect as fossil fuel-emitted CO_2~~molecules are all alike, fundamental differences in their origin suggest that the effects from fire emissions~~. However, major differences exist between the effects of fire vs. fossil fuel combustion on the global carbon cycle and ~~temperature are irreconcilable with the effects from fossil fuel emissions~~climate, because: 1) fossil fuel combustion implies a net transfer of carbon from geological reservoirs to the atmospheric, oceanic, and terrestrial pools, whereas fire does not; 2) the atmospheric lifetime of fire-emitted CO_2 is not the same as for fossil fuel-emitted CO_2; and 3) other impacts, for example on land surface albedo, also differ between fire and fossil fuel combustion. The main purpose of this study is to illustrate the consequences from these fundamental differences between ~~emissions from fossil fuels~~ fossil fuel combustion and non-deforestation fires (i.e., following which the natural vegetation can recover) using 1000-year simulations of a coupled climate–carbon model with interactive vegetation. We assessed emissions from both pulse and stable fire regime changes, considering both the gross (carbon released from combustion) and net (fire-caused change in land carbon, also accounting for vegetation decomposition and regrowth, as well as climate–carbon feedbacks) fire CO_2 emissions. In all cases, we found substantial differences from equivalent amounts of emissions produced by fossil fuel combustion. These findings suggest that side-by-side comparisons of non-deforestation fire and fossil fuel CO_2 emissions – implicitly implying that they have similar effects – should therefore be avoided, particularly when these comparisons involve gross fire emissions. Our results also support the notion that most net emissions occur relatively soon after fire regime shifts and then progressively approach zero~~, whereas~~

~~gross emissions stabilize around a new value that is a poor indicator of the cumulative net emissions caused by the fire regime shift~~. Overall, our study calls for the explicit representation of fire ~~in climate models, rather than resorting to ersatz results coming from fossil fuel simulations,~~ activity as a valuable step to foster a more accurate understanding of its impacts ~~in the Earth system~~on global carbon cycling and temperature, compared to conceiving fire effects as congruent with the consequences from fossil fuel combustion.

1 Introduction

~~Fire~~ Fossil fuel emissions entail a net transfer of carbon from geological reservoirs to the much more active atmospheric, oceanic, and terrestrial carbon pools, thereby increasing the total amount of carbon in these pools and leading to an atmospheric CO_2 anomaly that decreases only gradually on a millennial timescale (Archer et al., 2009; Eby et al., 2009; Joos et al., 2013) . This atmospheric CO_2 anomaly causes global warming that remains stable over thousands of years (Matthews and Caldeira, 2008; Eby et al., 2009) . The atmospheric CO_2 anomaly also gives rise to a global CO_2 fertilization effect that decreases land surface albedo, due to dynamic vegetation expansion and generally higher vegetation cover, with an additional warming resulting from this fertilization-induced albedo decrease (Matthews, 2007; Bala et al., 2013) .

Fire (also referred to as wildland fire, wildfire, and open vegetation burning) is a conspicuous disturbance in most terrestrial ecosystems, with considerable impacts on vegetation ~~itself, carbon cycling,~~ and climate (Bonan, 2008; Running, 2008; Bowman et al., 2009) . Contrary to fossil fuel combustion, fire does not entail a net addition of CO_2 to the three active carbon pools of the Earth System, but simply redistributes the carbon already existing within these global pools. Except when used for permanent land clearing, fire usually triggers a strong local-scale vegetation regrowth response lasting years to decades depending upon the ecosystem (van der Werf et al., 2003; Goulden et al., 2011) ; hence the resulting atmospheric CO_2 anomaly and the concurrent global CO_2

fertilization are of shorter duration than after fossil fuel combustion. Fire also causes major modifications to land–atmosphere exchanges ~~, and climate in general (Bonan, 2008; Running, 2008; Bowman et al., 2009) .~~ of energy through altered surface albedo and sensible/latent heat partitioning (Bremer and Ham, 1999; Amiro et al., 2006) . Besides a short-term decrease due to surface blackening, local albedo generally increases after a fire event, thereby leading to a regional-scale cooling that is consequential at the global scale (Ward et al., 2012; Landry et al., 2015a) . For the same amount of emitted CO_2, fire therefore differs from fossil fuel combustion in terms of: 1) the net addition of CO_2 to the active carbon cycling pools for fossil fuel combustion only; 2) average lifetime of CO_2 molecules in the atmosphere; and 3) non-CO_2 climatic impacts (e.g., albedo) that also affect the carbon cycle. Given that these differences are in fact inseparable from the CO_2 emitting process, we expect the same amount of CO_2 emissions from fire vs. fossil fuel combustion to have different effects on the global carbon cycle and temperature.

Fire currently affects around 300–500 Mha yr^{-1} (Mieville et al., 2010; Randerson et al., 2012; G leading to gross emissions ~~of 1.5–3from the direct~~ (i.e., accounting only for the combustion of vegetation and soil–litter~~(Kloster et al., 2010; Mieville et al., 2010; Thonicke et al., 2010; van der Werf et al., 2010; Ra~~ of 1.5–3 Pg C yr^{-1} (Mieville et al., 2010; van der Werf et al., 2010; Randerson et al., 2012) . The potential for modifications in the current fire regime to modulate climate change stimulated the explicit representation of fire in the Lund–Potsdam–Jena (LPJ) Dynamic Global Vegetation Model (DGVM; Thonicke et al., 2001), and later on into various other similar process-based models of climate–vegetation interactions (Arora and Boer, 2005; Kloster et al., 2010; Li et al., 2014) . These efforts have paved the way to studies that projected an increase in fire frequency and gross CO_2 emissions over the 21st century (Scholze et al., 2006; Pechony and Shindell, 2010; Kloster et al., 2012).

The net effect of fire on global carbon cycling has however received less attention than the consequences from future ~~climate–fire feedbacks~~changes in fire activity. In their seminal study, Seiler and Crutzen (1980) concluded that net biospheric emissions, coming mostly from fire, could range between $\pm 2\,\mathrm{Pg\,C\,yr^{-1}}$ by adding the effects of vegetation regrowth and other processes to their estimate of 2–4 $\mathrm{Pg\,C\,yr^{-1}}$ for gross fire emissions. The net effect of fire on global terrestrial carbon storage has then apparently been left unaddressed for more than three decades, until Ward et al. (2012) suggested a fire-caused net reduction of $\sim 500\,\mathrm{Pg\,C}$ in pre-industrial ~~global~~ land carbon. They also found that this reduction could currently be slightly lower (around 425 $\mathrm{Pg\,C}$) due to offsetting effects between fire and land-use and land cover changes (LULCC), but could increase to about 550–650 $\mathrm{Pg\,C}$ by the end of this century due to a climate-driven increase in fire activity. More recently, Li et al. (2014) concluded that net fire emissions were equal to 1.0 $\mathrm{Pg\,C\,yr^{-1}}$ on average during the 20th century, compared to gross emissions of 1.9 $\mathrm{Pg\,C\,yr^{-1}}$ on average over the same period. ~~The latter two studies were however performed in offline terrestrial models and were therefore unable to account for various climate–fire feedbacks, including fire-induced fertilization and the impact of changes in surface albedo on temperature. To date, the only study dedicated to fire in a coupled climate–carbon model with interactive vegetation dealt primarily with the consequences of major changes in future fire regime, but also found that net emissions following changes in fire regime quickly became much smaller than gross emissions and progressively decreased over time (Landry et al., 2015a) .~~

~~The dearth of studies dedicated to fire in coupled climate–carbon models has led to potentially inaccurate methods for estimating the climatic effects of~~ While the fact that vegetation regrowth offsets a fraction of gross fire emissions has been appreciated for some time, previous global quantifications of the difference between gross and net emissions have been performed with first-order estimates (Seiler and Crutzen, 1980) or in offline terrestrial models (Ward et al., 2012; Li et al., 2014) , and have neglected relevant processes. Indeed, net fire $\mathrm{CO_2}$ emissions ~~. Indeed, previous studies had to rely upon results from simulations of fossil fuel emissions in order to estimate the fate of fire-emitted (**??**) . A convenient way to proceed consists of combining fire-caused land–atmosphere exchanges based on empirical or offline modelling data with a fossil fuel-derived impulse response function (IRF). IRFs give the proportion of a single pulse of emissions that remain airborne as a function of time (t, in years) and are usually expressed as a sum of three decaying exponentials with a constant~~

~~term (Joos et al., 2013) :~~

$$\mathrm{IRF}(t) = a_0 + \sum_{i=1}^{3} a_i \times \exp(-t/\tau_i)$$

~~where $\{a_i\}$ are unitless and $\{\tau_i\}$ are in years. Such IRF-based approaches have also been used in other contexts, for example to quantify the fate of atmospheric~~ differ from gross emissions because they include not only the gradual decomposition of the non-trivial fraction of vegetation killed by fire but not combusted (especially for trees) and the post-fire vegetation regrowth, but also the effects of various feedbacks like the fire-induced CO_2 ~~anomalies resulting from boreal peatlands forestation (**?**) , boreal forest biofuels (**?**) , and other disturbances like insect outbreaks and hurricanes (**?**) . Yet in the case of fire at least, estimating carbon and temperature effects based on simulations of fossil fuel emissions appears questionable due to the major differences involved. First, fossil fuel emissions entail a net transfer of~~ fertilization of terrestrial vegetation, or the impacts on vegetation productivity and soil–litter decomposition of temperature changes caused by modified atmospheric CO_2 ~~from geological reservoirs to the much more active atmospheric, oceanic, and terrestrial carbon pools, whereas fire simply redistributes the carbon already existing in these three pools. Second, contrary to fossil fuel emissions, fire directly triggers a strong vegetation regrowth response and substantial modifications to land–atmosphere exchanges of energy through altered surface albedoand sensible/latent heat partitioning (Bremer and Ham, 1999; van der Werf et al., 2003; Amiro et al., 2006; Goulden et al., 2011)~~ and surface albedo.

In this study, we used a coupled climate–carbon model with interactive vegetation to advance the current knowledge regarding the effects of fire CO_2 emissions on the global carbon cycle and temperature. Using such a model allowed us to keep track of the total carbon in the Earth System, include the major role of the ocean in the fate of the fire-emitted CO_2, and account for the various feedbacks mentioned previously (i.e., CO_2 fertilization and temperature–CO_2 interactions), which are consequential for the global carbon cycle and temperature responses. We focussed on non-deforestation fires that allow the different vegetation types to compete and grow back in the recently burned area, because they constitute the bulk of global burned area and gross emissions (van der Werf et al., 2010) and have been much less represented in climate models than the LULCC events associated with deforestation fires. Our main objective is to compare the long-term effects of fire CO_2 emissions to corresponding levels of fossil fuel CO_2 emissions, for single fire pulses and stable fire regimes. A second objective is to quantify the differences between gross and net fire CO_2 emissions over 1000 years following major changes in fire frequency; note that the simulated net emissions accounted for all processes mentioned previously (i.e., decomposition of fire-killed vegetation, regrowth, global CO_2 fertilization, and temperature–CO_2 interactions on land and in the ocean) in addition to the gross (i.e., combustion) emissions. To facilitate the interpretation of results, we performed all simulations against a background climate corresponding to pre-industrial conditions.

2 Methods

2.1 Modelling of fire and fossil fuel effects

We used the University of Victoria Earth System Climate Model (UVic ESCM) version 2.9 to study the climatic effects of fire and fossil fuel CO_2 emissions. The UVic ESCM computes at a resolution of $3.6^\circ \times 1.8^\circ$ (longitude × latitude) the exchanges of carbon, energy, and water among the land, atmosphere, and ocean (Weaver et al., 2001; Eby et al., 2009). The land module consists of a simplified version of the MOSES land surface scheme (Meissner et al., 2003) coupled to the TRIFFID DGVM (Cox, 2001). TRIFFID simulates the competition among five different plant functional types (PFTs): broadleaf tree, needleleaf tree, C_3 grass, C_4 grass, and shrub, accounting for the dynamics of different carbon pools for vegetation (leaves, stem, and roots) and soil–litter. The UVic ESCM computes the atmospheric energy and moisture balance with dynamical feedbacks, and its ocean module represents three-dimensional circulation, sea ice dynamics and thermodynamics, inorganic carbon, and ecosystem/biogeochemical exchanges (Weaver et al., 2001; Ewen et al., 2004; Schmittner et al., 2008; Eby et al., 2009).

The UVic ESCM can account for various types of prescribed forcings, including the emissions of CO_2, other greenhouse gases, and sulphate aerosols, land cover changes, volcanic aerosols, and land ice (Weaver et al., 2001; Matthews et al., 2004). In this study, we also used the UVic ESCM fire module developed by Landry et al. (2015a). In each grid cell, this module estimated the gross CO_2 emissions coming from combustion as the product of prescribed burned area (see Sect. 2.2), fuel density (simulated by the UVic ESCM), and PFT-specific combustion fractions for the different fuel types (Table 1). The carbon contained in the vegetation killed by fire but not combusted was transferred to the soil–litter pool, where it decomposed and released additional CO_2 at a rate that depended upon the simulated soil temperature and moisture. Since we were interested in non-deforestation fires, the different PFTs could compete and grow back in the recently burned area, giving rise to a regrowth CO_2 flux influenced by the climate–carbon feedbacks simulated by the UVic ESCM (e.g., fire-induced CO_2 fertilization and temperature changes). The model further accounted for the post-fire changes in land surface exchanges due to the modified vegetation cover, including the increase in land surface albedo (α_L, unitless). In all simulations, we included only the ~~CO_2~~CO_2-related effects of fire and fossil fuel combustion, and not the associated aerosols and non-CO_2 greenhouse gases. We note that fire releases some carbon as carbon monoxide (CO) and methane (CH_4); however, these species constitute less than 10% of the fire-emitted carbon (Andreae and Merlet, 2001) and get mostly oxidized to CO_2 on a timescale shorter than the one of interest here (Ehhalt et al., 2001; Boucher et al., 2009) . Similarly, we did not include here the short-term albedo decrease due to surface blackening.

2.2 Prescribed burned area

We based the prescribed burned area on the January 2001 to December 2012 monthly data from version 4 of the Global Fire Emissions Database (GFED4), which was derived from satellite observations (Giglio et al., 2013). We then simplified the GFED4 dataset in order to retain its most essential features only. Each grid cell from the UVic ESCM was labelled as a “fire cell” if it had been affected by fire at least once over the 2001–2012 period according to GFED4 (Fig. 1). The main simplification here was that the burned area fraction was set equal across all the UVic ESCM fire cells, with the specific burned area fraction value varying across fire simulations (see Sect. 2.3). The use of this binary distribution of burned area fractions (i.e., the same value for all fire cells and zero for all other cells) was necessary in order to reach the target fire CO_2 emissions while ensuring that the burned area fractions were proportional for all fire cells across the different fire simulations. ~~(~~Given that the actual burned area fractions are already relatively close to 100 % in various regions (Giglio et al., 2013), upscaling the original GFED4 data would not have resulted in the same relative changes for all fire cells. ~~)~~Fire happened one time per year in each of the UVic ESCM fire cells, during the month of highest burned area according to the mean 2001–2012 value from GFED4 data (Fig. 1).

2.3 Simulation design

We started with an equilibrium run of the climate system for the year 1750, using the prescribed forcings from Eby et al. (2013) for solar radiation, atmospheric CO_2 (fixed at 277 ppmv), non-CO_2 greenhouse gases, land cover changes, land ice, and volcanic aerosols. Five groups of transient simulations then branched off from this equilibrated climate, in addition to a control transient simulation; in all cases, the forcings from year 1750 were maintained, except that the climate and carbon cycle were free to respond to the effects of the fire and fossil fuel experiments.

First, we performed three simulations that each consisted of a single year of fire activity, followed by a return towards the pre-fire equilibrium conditions. The resulting fire pulses had sizes of 20, 100, and 200 Pg C, based on their gross emissions (i.e., the carbon released from combustion only). We obtained these fire CO_2 pulses by adjusting the single-year burned area fraction across all fire cells and designate these simulations as Fire20P, Fire100P, and Fire200P.

Second, we performed another set of fire experiments similar to the previous ones, except that the same burned area fractions were maintained year after year. We designate these stable fire ~~regime~~ regimes as Fire20S, Fire100S, and Fire200S, corresponding to the previous fire pulse experiments of 20, 100, and 200 Pg C, respectively.

Third, we injected fossil fuel CO_2 pulses of 20, 100, and 200 Pg C into the atmosphere over a single year. The purpose of this set of three simulations was to compare the effects from fossil fuel CO_2 emissions vs. the same amount (and timing) of gross fire emissions. We designate these simulations as FF20P-G, FF100P-G, and FF200P-G.

Fourth, we wanted to compare the effects from fossil fuel CO_2 emissions vs. the same amount (and timing) of net fire emissions following each fire pulse. ~~In addition to the released by combustion, net fire emissions included post-fire vegetation regrowth, decomposition of the vegetation that was killed but not combusted, and climate–carbon feedbacks.~~ Each year, we computed the net fire emissions (land to atmosphere) as the annual change in total land carbon for the control simulation, minus the annual change in total land carbon following the fire pulse (Fire20P, Fire100P, or Fire200P). We then injected into the atmosphere yearly fossil fuel CO_2 emissions that were equal to these net fire emissions, including when they were negative (implying atmospheric carbon was sequestered back into geological reservoirs). We designate these simulations as FF20P-N, FF100P-N, and FF200P-N.

Fifth, we performed a set of three fossil fuel experiments in which the yearly fossil fuel CO_2 emissions were this time equal to the net emissions from the Fire20S, Fire100S, and Fire200S stable fire regimes. We designate this last set of simulations as FF20S-N, FF100S-N, FF200S-N.

3 Results

3.1 Assessment of the UVic ESCM fire module

The burned area fractions (unitless) in the fire cells for the 20, 100, and 200 ~~PgC~~ Pg C pulses were approximately equal to 0.09, 0.45, and 0.88, respectively. Since the 200 Pg C pulse led to the burning of almost all the area within the fire cells, we used the results of this simulation to assess the post-fire simulated responses for changes in PFT cover, total biomass, and α_{L} in different ecosystem types (Fig. 2). In northern forests, the succession among the different PFTs (Fig. 2a) ~~agreed with~~ was qualitatively similar to, but noticeably slower than, observation-based trajectories (Rogers et al., 2013)~~, while the impacts on~~. Simulated fire-caused changes also appeared reasonable when compared with field observations for biomass (Fig. 2c) (Goulden et al., 2011) and α_{L} (Fig. 2e) ~~were consistent with field observations (Amiro et al., 2006; Goulden et al., 2011) . The overall slower return to pre-fire conditions compared to observations came from the lasting climatic effects from the extreme 200fire pulse (see Sect. 3.2)~~(Amiro et al., 2006) . As expected (van der Werf et al., 2003; Ward et al., 2012), the return to pre-fire conditions was much faster in savannas (Fig. 2b, d, and f). Note that the very small increase in total biomass soon after the fire pulse (Fig. 2d) and the associated marginal decrease in α_{L} (Fig. 2f; not visible) likely came from the CO_2 fertilization effect caused by the long-lasting atmospheric CO_2 anomaly (see Sect. 3.2).

Additional simulations performed by Landry et al. (2015a) further established the realism of results from the UVic ESCM fire module. First, they obtained gross fire CO_2 emissions of 2.2 $\mathrm{Pg\,C\,yr^{-1}}$ for the current fire regime, comparable to previous studies (Kloster et al., 2010; Mieville et al., 2010; Thonicke et al., 2010; van der Werf et al., 2010; Randerson et al., 2012; Li et al., 2014). The splitting of these gross emissions between vegetation (0.7 $\mathrm{Pg\,C\,yr^{-1}}$) and soil–litter (1.5 $\mathrm{Pg\,C\,yr^{-1}}$) also agreed with GFED-based estimates (van der Werf et al., 2010). Second, the differences in α_{L} between the current fire regime and a no-fire world simulated by Landry et al. (2015a) led to a global radiative forcing of $-0.11\,\mathrm{W\,m^{-2}}$ without the effect of surface blackening and $-0.07\,\mathrm{W\,m^{-2}}$ with surface blackening, in agreement with observation-based estimates (Ward et al., 2012) (note that we did not include surface blackening in the current study).

3.2 Single fire pulse

The atmosphere, ocean, and land carbon pools responded as previously reported (Archer et al., 2009; Eby et al., 2009, 2013; Joos et al., 2013) to the fossil fuel CO_2 pulses (Fig. 3a). Part of the CO_2 injected into the atmosphere progressively became absorbed by the land and ocean, so that 1000 years after the pulses, 60 % of the additional CO_2 was ~~found into~~ taken up by the ocean and the remaining 40 % was divided almost equally between the land and atmosphere. The limited absolute difference among the pulse magnitudes studied here (i.e., 180 Pg C) explains why the responses were almost identical in the three cases, contrary to what has been found for a larger range of pulse magnitudes (Archer et al., 2009; Eby et al., 2009; Joos et al., 2013).

Fire effects (Fig. 3b) differed substantially from the fossil fuel pulse results. This time the CO_2 injected into the atmosphere came from the land, resulting in decreased land carbon rather than increased land carbon as in the case of fossil fuel. Instead of leading to long-lasting changes, the fire pulses were followed by a gradual return towards the initial equilibrium conditions. ~~These two features illustrate a fundamental distinction between fossil fuel and fire: fossil fuel emissions represent a near-permanent addition of to the active (i.e., non-geological) carbon cycling pools, whereas fire pulses temporarily reshuffle the carbon already existing in these pools.~~ Moreover, the responses varied noticeably among the three fire pulses. Finally, fractional changes greater than 1.0 were observed for the atmosphere and land shortly after the pulses because~~the net emissions (i.e., including~~ , due to the decomposition of the uncombusted vegetation killed by fire~~) were initially~~ , the net emissions were higher than the gross emissions upon which the magnitude of the pulses were defined.

Figure 3c compares the airborne fraction of the CO_2 pulses from fossil fuel vs. fire. All results were similar during ∼25 years following the pulses, and for up to ∼50 years for Fire100P and the different fossil fuel pulses. However, the airborne fraction became systematically higher for fossil fuel than for fire after about a century. ~~Consequently, the IRF~~

~~parameters differed considerably among the three fire pulses, as well as with the fossil fuel pulses (Table **??**). Even if the airborne fraction behaviour was more complex for fire than for fossil fuel (Fig. 3c), the goodness of fit between the IRFs and the corresponding data was similar for both types of pulses (Table **??**). Note that the physical meaning of the fire IRF parameters should not be over-emphasized, as the fit of a sum of exponential functions to data is notoriously sensitive to noise (**?**) .~~

These differences ~~in the effects from fire vs. fossil fuel emissions on the carbon cycle~~ then affected the global mean atmospheric surface temperature (T_s, in K), as shown in Fig. 4a. Fossil fuel $\mathrm{CO_2}$ emission pulses caused relatively stable increases in T_s over millennial timescales (Matthews and Caldeira, 2008; Eby et al., 2009). In the case of fire pulses, the return of atmospheric $\mathrm{CO_2}$ towards pre-fire levels (Fig. 3b) resulted in smaller warming of much shorter duration. Atmospheric $\mathrm{CO_2}$ even decreased below the control level $\sim$ 400–500 years after the pulses, which contributed to the observed long-term net cooling effect particularly visible for Fire200P. This slight decrease in atmospheric $\mathrm{CO_2}$ came from the long time needed before the ocean returned to the atmosphere all the carbon absorbed following the fire pulses.

Albedo was also involved in the diverging effects of fire vs. fossil fuel on T_s (Fig. 4b). Fossil fuel-induced $\mathrm{CO_2}$ fertilization slightly decreased α_L (Matthews, 2007) over the whole simulation period, whereas fire noticeably increased α_L for decades to centuries. Note that contrary to the situation illustrated in Fig. 2a, in some northern grid cells tree cover had not fully recovered yet to pre-fire levels 1000 years after the 200 Pg C fire pulse. This lasting increase in α_L contributed to the net cooling following the fire pulses.

All previous outcomes illustrate that the effects on the global carbon cycle and temperature from fire vs. fossil fuel $\mathrm{CO_2}$ emissions differ ~~fundamentally~~ for identical pulse magnitude defined in terms of gross (i.e., combustion only) fire emissions. Now, what if fossil fuel emissions were instead set equal to the net land-to-atmosphere emissions from fire year after year over the entire simulation, a situation where we expect fossil fuel emissions to better mimic the effects from fire emissions? In this case, the impacts on land carbon remained opposite because emissions came from the land for fire but not for fossil fuel; for the atmosphere, however, the CO_2 anomalies were ~~much~~ more similar (Fig. 5a vs. Fig. 3b)~~. Yet a closer look at the results reveals that the atmospheric anomalies were not actually equal (~~, though not identical as can be seen in Fig. 5b~~)~~. During the first ~ 250 years, these anomalies were systematically lower for fossil fuel because the vegetation absorbed a portion of the emitted CO_2, whereas for fire the net emissions already accounted, by definition, for vegetation regrowth, global CO_2 fertilization, and all climate–carbon feedbacks. As a result, the ocean absorbed more carbon for fire than for fossil fuel emissions (Fig. 5a vs. Fig. 3b).

Based on atmospheric CO_2 alone, one would thus expect T_s to be higher for fire than for fossil fuels, yet the opposite was in fact observed (Fig. 5c) due to the opposite impacts on α_L (Fig. 5d). Note that in the long term, these ΔT_s were however much smaller than when fossil fuel emissions were equal to gross fire emissions (Fig. 4a). The fact that atmospheric CO_2 anomalies became slightly lower for fire than for fossil fuel after about 250 years (Fig. 5b; not visible) can be explained by long-lasting impacts on ocean carbon cycling: compared with fossil fuel, the ocean absorbed substantially more carbon in the initial decades after the fire pulses, and then took more time to outgas this carbon when the atmosphere–ocean fluxes shifted sign during the return towards the initial equilibrium conditions.

3.3 Stable fire regime

The previous results ~~provide relevant information regarding fundamental differences between fire and fossil fuel emissions, but~~ were based on single pulses of fire activity~~. We~~ ; we now turn to stable fire regimes for which the burned area fraction was maintained year after year, instead of being applied only once as in the pulse experiments. Figure 6 shows that the resulting gross and net emissions had qualitatively similar behaviours for the three stable regimes. Both the gross and net yearly emissions decreased quickly after an initial spike. The yearly net emissions progressively stabilized close to zero, although their mean value was still positive towards the end of the simulations as indicated by the slight positive slope of the cumulative net emissions. The yearly gross emissions, on the other hand, stabilized around much higher values because vegetation and soil–litter kept being combusted each year. Contrary to net emissions, the cumulative gross emissions thus increased almost linearly ∼ 50 years after the onset of fire activity and onwards (results not shown).

Gross emissions thus appear highly inadequate to assess the cumulative impacts of fire regime shifts. Indeed, yearly gross emissions towards the end of the simulations were higher for Fire100S than for Fire200S, even though the outcome was obviously the opposite for the cumulative net emissions (Table 2). The lower land carbon density caused by more frequent fires has previously been observed to result in a "saturation effect" of gross emissions (Landry et al., 2015a); here, this effect was so large that gross emissions ended up being lower for Fire200S than for Fire100S about 50 years after the onset of fire activity. A similar saturation effect clearly affected the cumulative net emissions, which were only twice as large for Fire200S compared to Fire20S, whereas the equilibrium yearly burned area was 12 times larger for Fire200S vs. Fire20S (Table 2). This slightly supra-linear scaling in burned area (e.g., 12 times instead of 10 times larger for Fire200S vs. Fire20S) among stable fire regimes was caused by fire-induced changes in vegetation composition. The input prescribed burned area in each fire cell (see Sect. 2.2) actually corresponds to a gross value that is reduced to account for the PFT-specific unburned islands occurring within burn perimeters (Kloster et al., 2010; van der Werf et al., 2010). More frequent fires led to increases in grass cover at the expense of trees and shrubs, thereby increasing the net burned area. ~~The cumulative gross emissions at the end of the simulations were around 8, 23, and 21EgC for Fire20S, Fire100S, and Fire200S, respectively. These values were much higher than the corresponding cumulative net emissions (Fig. 6 and Table 2) – and, for the two most severe regimes, were in fact even higher than the estimated fossil fuel total resource base (**?**) . The injection of such amounts of fossil fuel into the atmosphere would obviously result in much more severe impacts on the carbon cycle and temperature (Matthews and Caldeira, 2008; Archer et al., 2009; Eby et al., 2009; Joos et al., 2013) than were observed for the three stable fire regimes.~~

Even for fossil fuel emissions that were equal to the net emissions from stable fire regimes, the effects differed once again. Figure 7a shows the distribution of net cumulative emissions (i.e., from year 0 until the specific year considered) from fossil fuel among the active carbon pools. This splitting was similar to the one following a single fossil fuel pulse (Fig. 3a), except that the maximum land uptake was proportionally lower and the ocean took a little longer to become the main carbon sink. For fire (Fig. ~~6b~~7b), land carbon rather decreased (with a fractional change equal to -1.0 as the net emissions were, by definition, equal to the total change in land carbon) and the uptake of carbon by the ocean had to be substantially higher than for fossil fuel.

The airborne fraction of the net emissions from stable fire regimes was initially higher than for the same amount of emissions from fossil fuel, but the anomalies in atmospheric CO_2 progressively became more similar (Fig. 8a). This should have caused T_s to be higher for fire than for fossil fuel, yet once again the opposite was observed (Fig. 8b). Cumulative fossil fuel CO_2 emissions led to T_s increases that were relatively stable over thousands of years (Matthews and Caldeira, 2008; Eby et al., 2009). For fire, on the other hand, the initial increase in T_s after the onset of fire activity was followed ∼ 50–100 years later by a gradual decrease in T_s. As was the case for the pulse simulations (see Sect. 3.2), this ~~opposite effect of fire vs. fossil fuel emissions~~ different effect on T_s ~~was related to~~ came from opposite changes in land albedo, which substantially increased for fire due to changes in vegetation cover, but slightly decreased for fossil fuel due to CO_2 fertilization (Fig. 8c).

4 Discussion

4.1 Fundamental differences between fire and fossil fuel

In this study, we have shown a consistent pattern of fundamental differences between the carbon cycle and climate effects of CO_2 emitted by fire as compared to fossil fuel combustion, which ultimately came from the net addition of CO_2 by fossil fuel combustion (contrary to fire), as well as the differences in atmospheric lifetime of emitted CO_2 and in non-CO_2 climatic impacts. First, the sources of CO_2 emissions are qualitatively distinct: fire simply reshuffles carbon among the active pools, whereas fossil fuel combustion entails a net carbon transfer from the geological to the active pools over millennial time scales (Archer et al., 2009; Eby et al., 2009). Second, the terrestrial pools (vegetation plus soil–litter) cannot respond in the same way to the atmospheric CO_2 anomalies created by fire vs. fossil fuel emissions. The only direct effect (i.e., excluding climate change) of fossil fuel emissions on land carbon storage occurs through the CO_2 fertilization effect. Fire, on the other hand, gives rise to a much more dynamic land carbon response. ~~The~~ Fire activity not only leads to CO_2 emissions through the combustion of land carbon and the further decomposition of killed but uncombusted vegetation~~constitute not only sources of fire emissions~~, but also ~~decrease~~ decreases the amount of vegetation that can instantaneously be fertilized by the fire-induced increase in atmospheric CO_2. Subsequently, however, vegetation regrowth and the associated soil–litter build up in the burned patches act as strong carbon sinks. Third, these contrasting effects on terrestrial vegetation mean ~~opposing~~ opposite changes in land albedo: fire-induced decrease in vegetation cover increases α_L, whereas fossil fuel-induced CO_2 fertilization decreases α_L through dynamic vegetation changes like increased shrub and tree cover in tundra (Matthews, 2007) and generally higher leaf and stem area index for the vegetation already in place (Bala et al., 2013). This divergence in α_L responses implies unequal T_s changes, which then feed back to affect the carbon cycle itself. Therefore, the effects on carbon cycling and temperature are incongruent even when fossil fuel emissions are equal to the net emissions from fire.

Other variables than carbon pools and α_L were affected by these different changes in T_s and amplified them. Sea ice area, for example, often diverged noticeably between corresponding fossil fuel and fire simulations. For FF100P-G and FF200P-G, there was a small ($\sim 2\,\%$ and $\sim 4\,\%$, respectively) but permanent decrease in global sea ice area that did not occur in the corresponding fire simulations. For FF100P-N and FF200P-N, sea ice area also decreased a little for a few centuries at least before gradually returning toward initial levels. (For FF20P-G and FF20P-N, the changes in global sea ice area were indistinguishable from internal variability.) For fire pulses, on the other hand, the substantial $\Delta\alpha_\mathrm{L}$-based cooling over the Northern Hemisphere due to extensive land masses slightly increased Arctic sea ice area; note that $\Delta\alpha_\mathrm{L}$ had a much smaller absolute influence on Antarctic sea ice, for which the changes were highly variable spatially. Such transfer of α_L-induced cooling to the surrounding ocean has also been observed following deforestation simulations, along with an additional decrease in atmospheric temperature over most latitudes resulting from the lower ocean temperature (Davin and de Noblet-Ducoudré, 2010). In our simulations of stable fire regimes and the corresponding fossil fuel experiments, changes in sea ice area were much larger due to higher net CO_2 emissions. For fossil fuel, sea ice area was permanently reduced in all simulations. For fire, the $\Delta\alpha_\mathrm{L}$-based cooling was not strong enough this time to prevent major losses of both Arctic and Antarctic sea ice, because the atmospheric CO_2 anomalies were larger and longer-lasting than following a single fire pulse. However, the increase in α_L helped maintaining lower temperatures for the stable fire regimes than for the corresponding fossil fuel simulations, and global sea ice area progressively recovered to the control level, albeit with spatial differences between the Arctic and Antarctic that matched the hemispherical changes in atmospheric temperature.

~~These fundamental differences imply that fire impacts cannot be accurately estimated from simulations of fossil fuel emissions in climate models. We already illustrated the validity of this claim for fossil fuel emissions that were equal to the net emissions from fire, for single fire pulses (Fig. 5) and stable fire regimes (Fig. 8). Here, we further assess two other adjustments based on approaches that have been used in previous studies of single fire events. The first approach consists of performing an offline estimate of the land–atmosphere fluxes triggered by fire, and then estimating the oceanic uptake of the remaining atmospheric anomaly based on atmosphere–ocean exchanges following the injection of a fossil fuel pulse in a climate model (**?**) . We reproduced this approach by combining results from the UVic ESCM simulations of fire (land–atmosphere fluxes) and fossil fuel (atmosphere–ocean fluxes) pulses. As shown in Fig. **??**a, this approach substantially underestimated the fire-caused atmospheric anomalies compared to the actual results from the UVic ESCM. The second approach consists of performing an offline estimate of the yearly land–atmosphere fluxes triggered by fire, and then applying an IRF obtained from fossil fuel simulations to each of these yearly land–atmosphere fluxes (**?**) . We reproduced this approach by combining the UVic ESCM land–atmosphere fluxes from fire simulations with the appropriate fossil fuel IRF from Table **??**, depending upon the~~

~~magnitude of the fire pulse. The bias for this second approach was initially even more negative, but decreased quickly following vegetation regrowth and ended up being slightly positive (Fig. **??**b). In fact, the results from this second approach were very similar to the ones obtained from fossil fuel emissions that were equal to net fire emissions (Fig. 5b). Note that our assessment of these two fossil fuel-based adjustments was conservative, because the UVic ESCM results we used for the land–atmosphere fluxes actually accounted for climate–fire feedbacks in a much more comprehensive way that offline simulations could do.~~

4.2 Study limitations

The outcomes of our study should be interpreted with ~~four~~ five caveats in mind. First, we developed idealized fire regimes in order to obtain substantial fire impacts while facilitating the comparison of results across the different magnitudes of pulses or stable regimes. Our fire regimes were therefore more severe than the current situation on Earth, as seen with our equilibrium results of $\geq 0.9\,\mathrm{Gha\,yr^{-1}}$ for burned area and $\geq 7.3\,\mathrm{Pg\,C\,yr^{-1}}$ for gross emissions under stable regimes (Table 2), vs. current values of 0.3–0.5 $\mathrm{Gha\,yr^{-1}}$ (Mieville et al., 2010; Randerson et al., 2012; Giglio et al., 2013) and 1.5–3 $\mathrm{Pg\,C\,yr^{-1}}$ ~~, respectively (Kloster et al., 2010; Mieville et al., 2010; Thonicke et al., 2010; van der Werf et al., 2~~ respectively. Moreover, our “equal” spatial fire patterns (i.e., same burned area fraction in each fire cell) gave much more weight to fires in extra-tropical regions compared with the current fire distribution (Giglio et al., 2013). Despite the differences in vegetation regrowth and fire-caused changes in albedo among regions, the impacts on atmospheric CO_2 and T_s did not seem overly sensitive to changes in the distribution of burned area fraction among fire cells following a single fire pulse (Fig. 9).

Second, we neglected all non-CO_2 emissions from fire and fossil fuel. Accounting for ~~fire non-emissions would reduce the albedo cooling effect, due to~~ the short-term post-fire surface blackening caused by char would reduce the albedo cooling effect. On the other hand, explicitly tracking all the patches created by individual fire events, instead of representing their average grid-level effect as we did here, would increase the simulated albedo cooling effect over boreal forests at least (Landry et al., 2015b), although the impact would likely be minor for the Fire200P and Fire200S simulations in which the burned area fraction was close to 90 % in each fire cell. Furthermore, the fire-caused emissions of aerosols and non-CO_2 greenhouse gases into the atmosphere would have a much stronger impact on T_s than changes in surface albedo; however, the magnitude and even the sign of the climatic effect from these non-CO_2 atmospheric emissions remain highly uncertain (Jacobson, 2004, 2014; Jones et al., 2007; Unger et al., 2010; Ward et al., 2012; Landry et al., 2015a). Future studies on the differences in the carbon cycling and temperature impacts between fire and fossil fuel would nevertheless benefit from ~~combining~~ considering the effects of non-CO_2 emissions~~with climate–carbon feedbacks in climate models including interactive vegetation~~.

Third, the UVic ESCM does not currently simulate the non-trivial exchanges of carbon between land and ocean (Regnier et al., 2013) or between inland waters and the atmosphere (Raymond et al., 2013), which are also impacted by fire. For example, the land-to-ocean flux of all particulate and dissolved pyrogenic carbon could be as high as ~ 50–$100\,\mathrm{Tg\,C\,yr^{-1}}$ (Bird et al., 2015). More research is therefore needed to accurately represent the highly variable and poorly quantified fate of such exchanges of pyrogenic carbon~~in climate models~~; meanwhile, their influence on our results is speculative, but is unlikely to challenge the main outcomes we obtained.

Fourth, the quantitative results we obtained were dependent upon the specific features of the UVic ESCM. For example, the simulated post-fire vegetation regrowth appeared too slow in northern grid cells (Fig. 2a), thereby overestimating the duration of both the α_L-based cooling and CO_2-based warming following fire. The carbon–concentration feedback parameters from the UVic ESCM are close to the mean from other fully coupled climate–carbon models, but its carbon–climate feedback parameters are on the high end (Arora et al., 2013) , meaning that the atmospheric CO_2 levels were more affected by temperature changes than would have occurred in most other models. Once again, these factors should not challenge the main outcomes we obtained.

Fifth, our study addressed only non-deforestation fires after which the natural vegetation is free to recover. One might argue that our stable fire regimes are similar to deforestation fires because, over large spatial scales, both fire types decrease terrestrial carbon storage and vegetation cover. However, our non-deforestation fires affected equally all fire cells, whereas deforestation fires are deemed exclusive to tropical regions (van der Werf et al., 2010). Given that fire-induced changes in terrestrial carbon density and albedo vary substantially among regions, we caution against the direct extrapolation of our results to deforestation fires. In fact, when neglecting non-CO_2 emissions, deforestation fires are conceptually more similar to other sources of LULCC than to non-deforestation fires. Note that previous global-scale climatic studies of LULCC (see Pongratz et al., 2014 for an extensive list) have represented all LULCC sources in the same way. Yet the variations in delayed CO_2 fluxes between fire and other LULCC sources matter for carbon cycling (Ramankutty et al., 2007; Houghton et al., 2012) and, as mentioned previously, non-CO_2 emissions could have a dominant impact on the climate. Consequently, studies dedicated to deforestation fires that specifically represent their delayed CO_2 fluxes and go beyond CO_2 emissions would allow for a more refined understanding of their climatic impacts.

5 Conclusions

The main purpose of this study was to illustrate the fundamental differences in the effects from fire vs. fossil fuel CO_2 emissions on the global carbon cycle and temperature. To do so, we simulated fire pulses and stable fire regimes of various magnitudes, as well as the corresponding fossil fuel emissions. The main outcomes we obtained were the following.

- The carbon sink stemming from vegetation regrowth led to widely diverging long-term impacts on the carbon cycle and temperature when fossil fuel emissions were equal to the gross emissions (i.e., based on combustion only) from a fire pulse, with the ~~opposing~~ opposite changes in land surface albedo further compounding these discrepancies (Figs. 3 and 4~~, and Table **??**~~). Side-by-side comparisons of gross fire CO_2 emissions to fossil fuel emissions are thus misleading and should be avoided.

- The impacts still differed, although much less severely, when fossil fuel emissions were equal to the net emissions following a fire pulse (Fig. 5). These results point towards the existence of irreconcilable disparities between the effects from fire vs. fossil fuel~~, a claim that was also supported by the shortcomings of two other possible adjustments aiming to estimate fire effects based on simulations of fossil fuel emissions in climate models (Fig. **??**)~~.
- Obvious differences also arose when fossil fuel emissions were equal to the net emissions caused by stable fire regimes, particularly for land carbon, oceanic carbon, surface temperature, and land surface albedo (Figs. 7 and 8).

Our results also shed light on the evolution of gross vs. net fire emissions following fire regime changes. ~~While~~ As expected, non-zero gross emissions were maintained indefinitely following a stable fire regime change, whereas most of the net emissions actually occurred relatively quickly after the regime shift and ~~net emissions~~ progressively decreased to almost zero (Fig. 6). ~~These results illustrate how inadequate it would be to represent the effects of fire regime changes by fossil fuel emissions equal to gross fire emissions.~~ Furthermore, a higher increase in fire frequency could result in lower equilibrium gross emissions due to the fire-induced decrease in the amount of fuel available (Table 2). Changes in gross emissions offered therefore a poor indicator of fire impacts on the carbon cycle.

Fire is arguably the most relevant disturbance in terrestrial ecosystems, with major impacts on carbon cycling and climate (Bonan, 2008; Running, 2008; Bowman et al., 2009). ~~Yet many studies of fire effects on these crucial elements have resorted to simulations of fossil fuel emissions in climate models.~~ The overarching message from the present study is that fire effects cannot be obtained from, and should not be conceived as akin to, fossil fuel emissions – rather, fire deserves its own explicit representation in ~~Earth system models~~climate-related studies.

Author contributions. J.-S. Landry and H. D. Matthews designed the study, J.-S. Landry modified the UVic ESCM with advice from H. D. Matthews, J.-S. Landry performed the simulations and analyzed the results, J.-S. Landry prepared the manuscript with contributions from H. D. Matthews.

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Table 1. Combustion fractions (all unitless) for the different PFTs (BT = broadleaf tree; NT = needleleaf tree; C3G = C_3 grass; C4G = C_4 grass; SH = shrub) and temporarily unvegetated portion of the grid cell (UNVEG). n/a: not applicable.

Fuel type	BT	NT	C3G	C4G	SH	UNVEG
PFT stem	0.30	0.30	0.95	0.95	0.30	n/a
PFT leaves	0.90	0.90	0.95	0.95	0.90	n/a
PFT roots	0.00	0.00	0.00	0.00	0.00	n/a
Soil–litter	0.12	0.12	0.05	0.05	0.10	0.05*

* The unvegetated fraction can be affected by fire only when the prescribed burned area is greater than the area covered by the five PFTs.

~~Comparison of the IRF for fossil fuel and fire pulses of 20, 100, and 200. For fire, the pulses correspond to the emissions from direct combustion only. The first two years were discarded from the IRF estimation, because the atmospheric anomaly sometimes reached its maximum value in the third year for fire. The sum of the four a_i was constrained to 1.0 for fossil fuel, but not for fire. See Eq. (1) for the seven parameters (a_i are unitless, τ_i are in years). R^2: coefficient of determination; MBE: mean bias error; RMSE: root mean square error.~~

~~Element2010020020100200a_0 0.177 0.183 0.178 0.011 -0.010 -0.018 a_1 0.131 0.140 0.146 -3.791 0.333 0.125 a_2 0.174 0.219 0.198 3.942 0.175 0.640 a_3 0.518 0.458 0.477 1.222 0.961 0.949 τ_1 362.0 280.8 335.1 351.0 121.9 242.6 τ_2 22.3 18.4 22.3 337.6 56.6 76.0 τ_3 5.1 4.9 5.4 9.2 5.9 3.5 R^2 0.9988 0.9997 0.9996 0.9976 0.9995 0.9980 MBE 2.9×10^{-6} -5.2×10^{-6} 9.8×10^{-6} -5.2×10^{-6} -2.9×10^{-6} -5.0×10^{-6} RMSE 0.002 0.001 0.001 0.004 0.003 0.007~~

Table 2. Burned area and emissions* for the three stable fire regimes.

Regime	Burned area (~~Gha~~Gha yr^{-1})	Gross emissions (~~PgC~~Pg C yr^{-1})	Cumulative net emissions (~~PgC~~Pg C)
Fire20S	0.9	7.3	629
Fire100S	5.4	21.1	966
Fire200S	10.8	18.9	1338

* Yearly results are the mean values over the last 60 years of simulation, whereas the cumulative net emissions are for the entire simulation. The onset of fire activity happened on year 0, after which fire frequency remained constant.

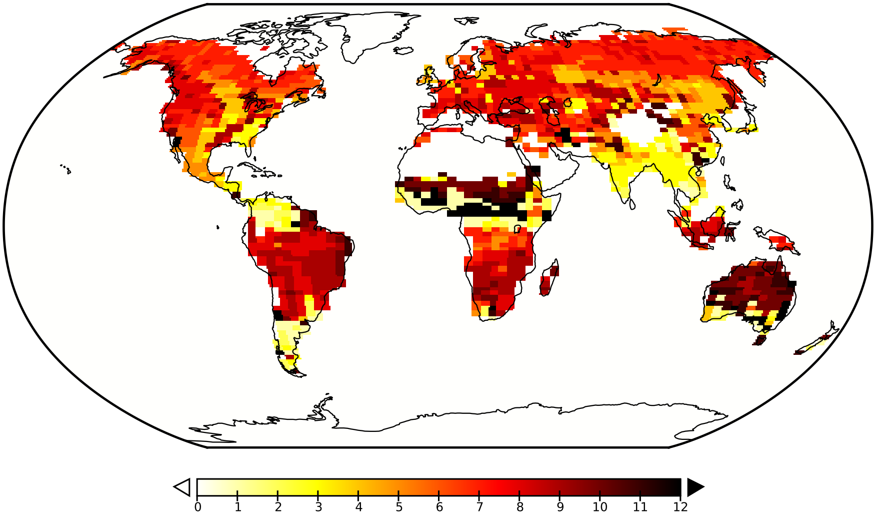

Figure 1. "Fire cells" used in the fire simulations. Numbers from 1 to 12 give the month of the year when fire occurs, whereas number 0 corresponds to grid cells without fire.

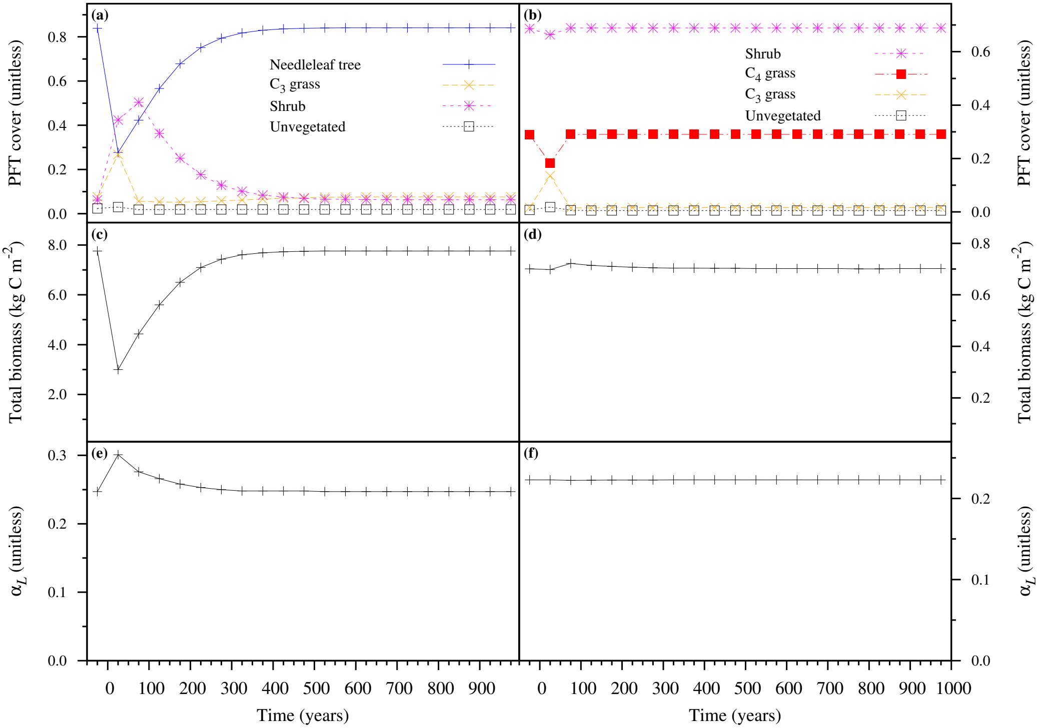

Figure 2. Changes due to the 200 Pg C fire pulse happening on year zero; each data point gives the mean value over 50 years (25 years before and 25 years after). Results are for a forested grid cell in North America (centered on 53.1° N, 124.2° W; panels **a**, **c**, and **e**) and a savanna grid cell in Africa (centered on 13.5° N, 12.6° E; panels **b**, **d**, and **f**). **(a, b)** Fractional cover of the different plant functional types. **(c, d)** Total biomass. **(e, f)** Land surface albedo.

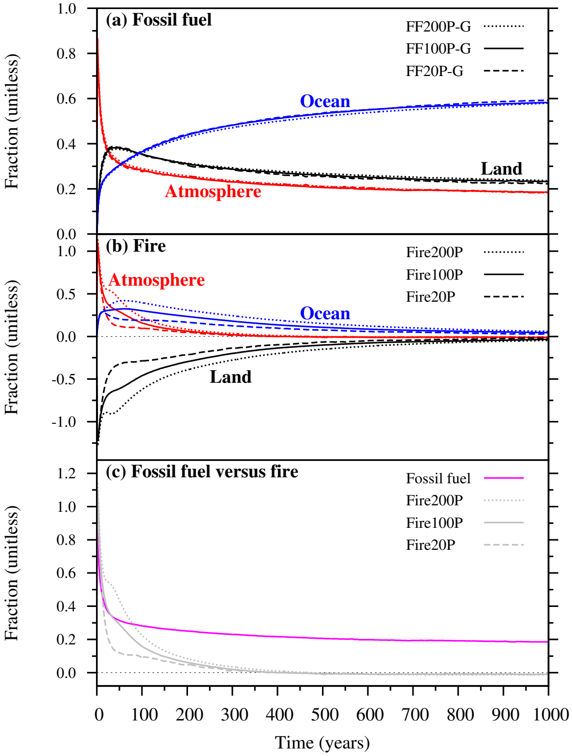

Figure 3. Changes in global carbon stocks resulting from the pulse experiments, expressed as fractions of each pulse magnitude. **(a)** Fossil fuel pulses, which were set equal to gross fire emissions. **(b)** Fire pulses. The fractions were sometimes greater than 1.0 for the atmosphere and land, because pulses were defined based on direct combustion only. **(c)** Results for atmospheric carbon only (i.e., airborne fraction); for fossil fuel, only FF100P-G is illustrated as the results were almost equal for the FF20P-G and FF200P-G cases (see panel **a**).

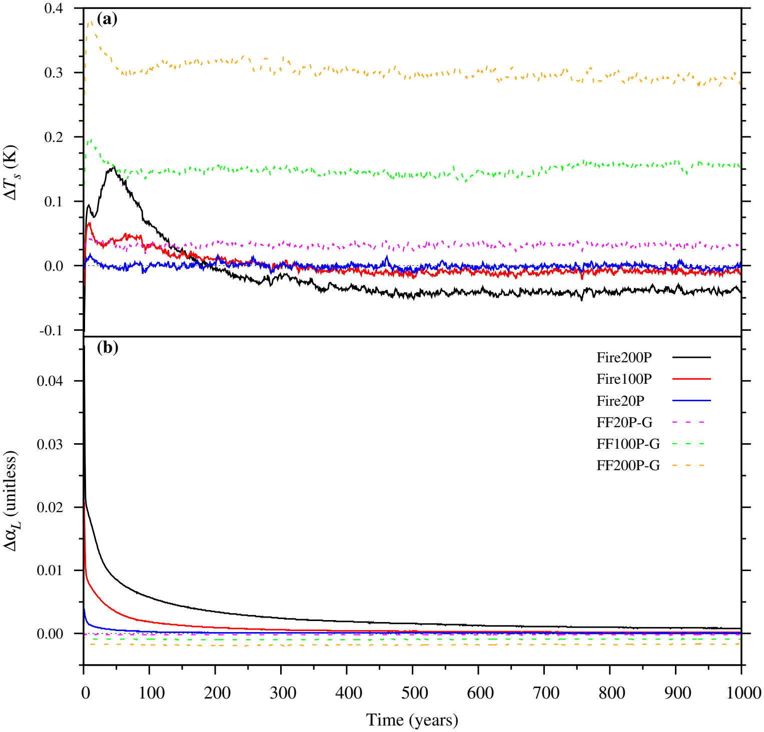

Figure 4. Changes in **(a)** global mean atmospheric surface temperature and **(b)** global mean land surface albedo from the pulse experiments. The fossil fuel emissions were set equal to gross fire emissions.

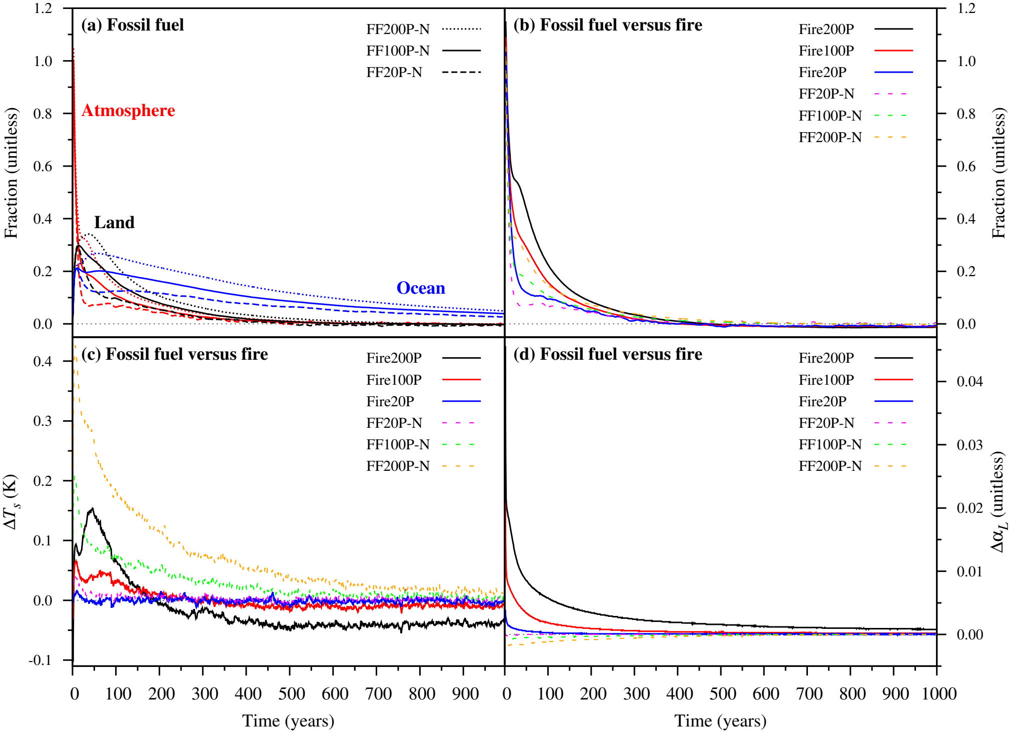

Figure 5. Effect of fossil fuel emissions set equal to net fire emissions. **(a)** Changes in global carbon stocks, expressed as fractions of each fire pulse magnitude. **(b)** Comparison with fire for the total atmospheric carbon, expressed as a fraction of each fire pulse magnitude. **(c)** Comparison with fire for the global mean atmospheric surface temperature. **(d)** Comparison with fire for the global mean land surface albedo.

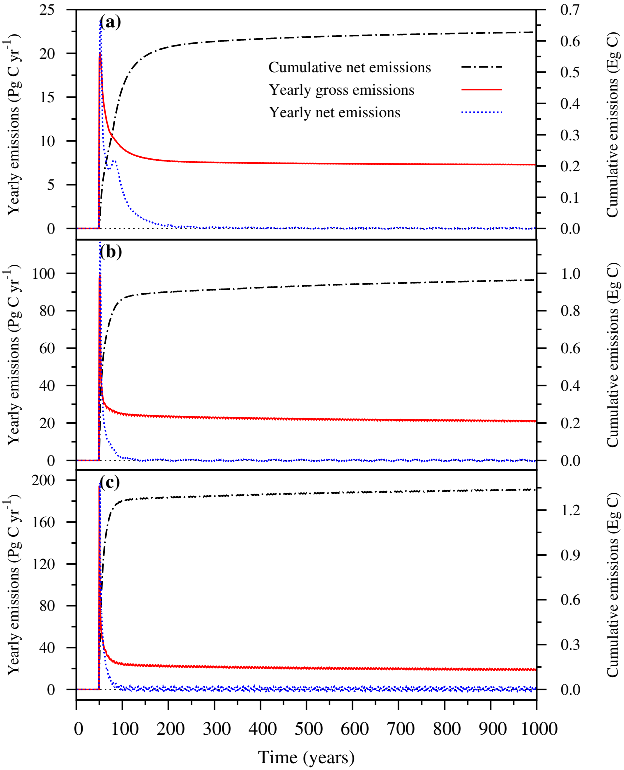

Figure 6. Yearly (both gross and net; left axis) and cumulative (right axis; 1 Eg C = 1000 Pg C) carbon emissions for the stable fire regimes. The onset of fire activity happened on year 0, after which fire frequency remained constant. **(a)** Fire20S. **(b)** Fire100S. **(c)** Fire200S.

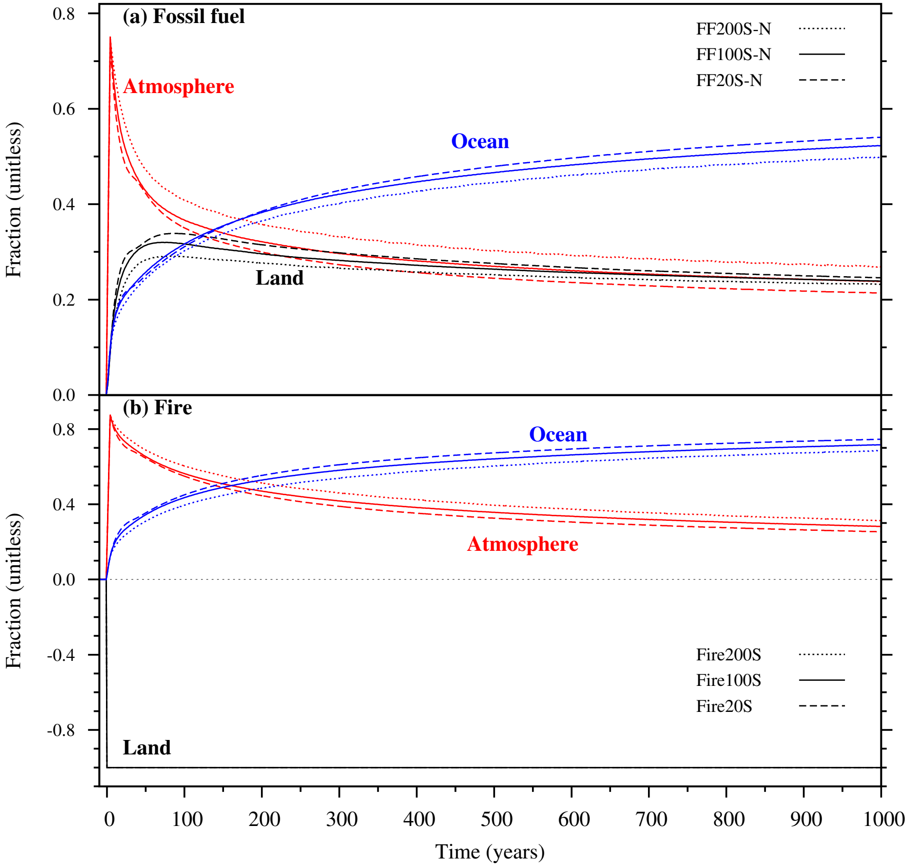

Figure 7. Changes in global carbon stocks resulting from the stable regime experiments. The changes are expressed as fractions of net cumulative emissions until the specific year considered. **(a)** Fossil fuel emissions, which were set equal to net yearly fire emissions. **(b)** Stable fire regimes; the onset of fire activity happened on year 0, after which fire frequency remained constant.

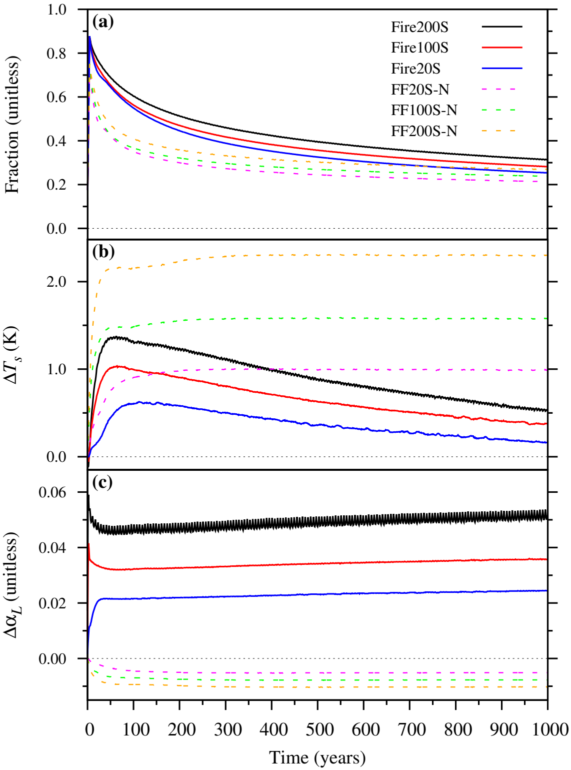

Figure 8. Changes in **(a)** atmospheric fraction of net cumulative emissions, **(b)** global mean atmospheric surface temperature, and **(c)** global mean land surface albedo from the stable regime experiments. The fossil fuel emissions were set equal to net yearly fire emissions.

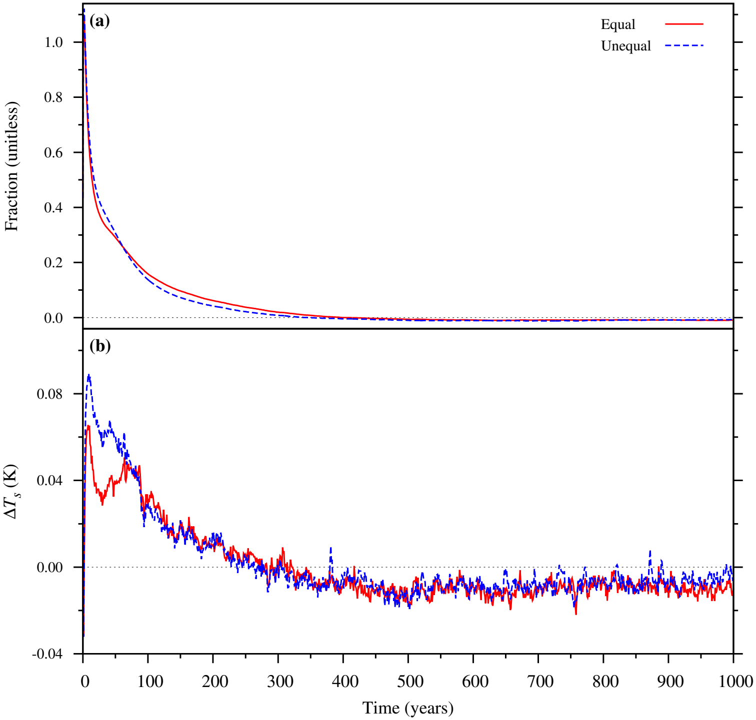
(a)
Equal
Unequal
Fraction (unitless)
1.0
0.8
0.6
0.4
0.2
0.0
(b)
ΔT_s (K)
0.08
0.04
0.00
-0.04
0
100
200
300
400
500
600
700
800
900
1000
Time (years)

Figure 9. Differences ~~in fire-caused atmospheric anomaly~~ between ~~adjustments based on fossil fuel simulations (see text for explanations) and the actual results from~~ two distinct spatial patterns of fire ~~simulations, expressed as fractions~~ pulses both resulting in gross emissions of 100 Pg C. For the “equal” pattern, the burned area fraction was the same in each ~~pulse magnitude~~fire cell. ~~Positive values mean that~~ For the ~~atmospheric anomaly~~ “unequal” pattern, the burned area fraction was two times higher ~~for fossil fuel-based adjustments~~ between 27° S and 27° N than for ~~the actual fire results~~other latitudes. **(a)** ~~Adjustment resorting to~~ Airborne fraction of the ~~atmosphere–ocean fluxes from fossil fuel simulations~~fire pulse. **(b)**~~Adjustment resorting to the IRF from fossil fuel simulations~~Change in global mean atmospheric surface temperature.

~~Differences between two distinct spatial patterns of fire pulses both resulting in gross emissions of 100. For the “equal” pattern, the burned area fraction was the same in each fire cell. For the “unequal” pattern, the burned area fraction was two times higher between 27S and 27N than for other latitudes. **(a)** Airborne fraction of the fire pulse. **(b)** Change in global mean atmospheric surface temperature.~~