Interactive comment on "Modelling the role offires in the terrestrial carbon balance by incorporating SPITFIRE into the global vegetation model ORCHIDEE – Part 2: Carbon emissions and the role of fires in the global carbon balance" by C. Yue et al.

Anonymous Referee #1
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Yue et al. present model results of the impact of fires on the global carbon cycle from simulations with SPITFIRE running inside ORCHIDEE. This paper focuses on carbon emissions from fires and the effect of fires on the terrestrial carbon sink, building off of a companion paper that introduces the model coupling and assesses model performance with regard to fire area burned. The model fire emissions are validated against the GFED although deforestation and agricultural fires are not included in this version of SPITFIRE. This makes the comparison difficult in many respects, in particular the fuel consumption is vastly different between the model and the GFED. The authors do a nice job pointing out this major caveat wherever relevant and make the comparison to GFED natural-fires-only where possible.

The analysis of changes in the terrestrial carbon sink uses the "fire-induced sink reduction" extensively and I find the use of this metric to be an effective way to look at the impacts of fire on the carbon cycle. The authors introduce the idea of a fire "respiration equivalence" which I think is an interesting concept, although I have some suggestions below on how to place this in a clearer context. Overall the paper is nicely presented with appropriate and effective figures, and I list suggestions for improvements below, mostly minor in nature.

[Response] We thank the reviewer for the efforts and the general positive comment on our work. Please find our detailed responses below each of the comments. To facilitate the reading, we marked all modified text in the updated manuscript in red.

General comments:

1. Although this is a companion paper, it would be helpful to the reader who is not familiar with this version of SPITFIRE to include a brief description (one-two paragraphs) of the major aspects of the model somewhere in Section 2. The combustion completeness is discussed in detail but there are a few other things that came to my mind while reading: how does the model treat fire-caused mortality, how are human impacts on fires included (i.e. changes in ignition based on population density but no fire suppression).In addition to these topics, which both come up in subsequent comments here, a basic description of how the model predicts fire events/spread would be helpful.

[Response] Following the reviewer's suggestion we now add two paragraphs in section 2.1, in which brief descriptions of fire physics and the SPITFIRE model and are presented.

2. The definitions of the land-atmosphere carbon fluxes in Section 2.4 could be simplified in my view. The use of both NEP and NBP seems to be superfluous since NEPOFF is the same as NBPOFF, given that the subscript "OFF" implies no fire carbon emission. If only NBP is

used, the SRFIRE equation can be simplified to "SRFIRE=NBPOFF –NBPON" so that it is clear that the SRFIRE is the difference of the same quantity from the two simulations (fire on and fire off). Maybe there is a reason for using both NEP and NBP that I am not seeing, but to me this seems a more clear way to express this quantity.
[Response] We think that the use of NBP_{OFF} rather than NEP_{OFF} in case of fireOFF simulation could potentially reduce the unnecessary complexity. According to the reviewer's suggestion we changed it, and all relevant terms and expressions are now updated in the text.

3. The idea of a "fire respiration equivalence" in the model is interesting, however I think the presentation of this concept could use more explanation. Firstly, Fig. 9d shows that, with the exception of one recent year, SRFIRE is always positive. This should mean that, while increased heterotrophic respiration (RH) in the FireOFF case may compensate for some of the enhanced sink without the fire C flux, it only very rarely compensates for all of the enhanced sink, not only when the fire year was extreme (Pg 9036, Lines 16-19)? If this is the case maybe it would be better to remove references to an "equivalence" and use an alternative description, such as "large-part compensation". Although this does not have the same simplicity of concept even if it may be more appropriate.

Also, some references to the respiration equivalence I think may give the wrong impression about the difference between the real world and a fire/no-fire world comparison. For example, Pg. 9019 Lines 18-19 reads ": : :fires mainly compensate the heterotrophic respiration that would happen if no fires had occurred." I think this gives the impression that in any given year if fires were suddenly turned off then, because of the increase in HR, about the same amount of carbon would be emitted as if fires were still turned on. In this case of the sudden fire switch off, while litter C might increase a bit, and RH with it, it would be a much smaller increase than is seen in a "no-fire" world that has had many years of litter C build-up, such as the FireOFF case in this study. In other words, the RH compensation might only matter relative to a "no-fire" world. So the phrase in the abstract "if no fires had occurred" might be better stated as "in a world without fires". This may seem like a subtle point to make but it is important in my view since readers may get the two ideas confused.
[Response] We agree with the reviewer that the "fire respiration equivalence" might give the impression that emissions are always equal to the excessive respiration in the fireOFF case, which is not true. Therefore we changed this phrase to "fire respiration partial compensation" to indicate the fact that it only partly compensates for the reduction of heterotrophic respiration in fireON case. All relevant expressions are modified in the text.

As pointed out by the reviewer, the expression in Lines 18-19 is indeed a little confusing. We changed it to "in a world without fire" to make the distinction from the case that fires are only turned off few years from a model run with fire.

Specific comments:
Pg 9023, Line 16: The fuel consumption timescale "h" may not be familiar to some readers and could use a definition here.

[Response] We added the following sentence in the 4th paragraph of section 2.1: "The categorization of fuels in terms of magnitude of hours describes the order of magnitude of time required to lose (or gain) 63% of the fuel moisture difference with the equilibrium moisture state under defined atmospheric conditions (Thonicke et al., 2010)."

Pg 9025, Line 23: It might be worth adding here that using constant land cover will mean not only that fires associated with land cover change (deforestation fires) will not be included but also that wildfires will not be affected by changing PFTs.
[Response] We added this sentence in the first paragraph of section 2.3: "The fire-vegetation-climate feedback was not included because the relative fractions of different PFTs remain the same over the simulation period. It means not only that fires associated with land cover change (deforestation fires) are not be included, but also that wildfires are not be affected by changing PFTs."

Pg 9026, Lines 9-10: It is not clear to me how the model as described here is capturing deforestation fires. This should be elaborated on, especially since prior statements indicate that deforestation fires are not included.
[Response] This is now elaborated in the same paragraph where the reviewer raises this comment (2nd paragraph of section 2.3).

Pg 9026, Line 26: Here is where I wondered how population density was taken into account when predicting fire events. A short description of the model in Section 2 would clarify this.
[Response] This is now included in section 2 by adding another two paragraphs describing fire modeling processes.

Pg 9026, Lines 16-26: The criteria for determining model equilibrium is mentioned briefly later on in this section (Pg 9027, Lines 15-17) but it would be helpful to include a description of the criteria used here on Pg 9026 when the spinup is being explained.
[Response] The following sentence is added in the 3rd paragraph of section 2.3, where the spin-up is being explained: "We verify that during last 50 years of this second spin-up, the mineral soil carbon stock varies within 0.1% and no significant trend exists for simulated global carbon balance."

Pg 9028, Lines 22-24: The authors could make more of an effort here to note that peatland fires are not exclusively anthropogenic (especially in N. Hemisphere high latitudes) even though it is convenient to group them this way for the purposes of the study.
[Response] We added the following explanations at the end of the paragraph: " Note that the grouping of different fire types in GFED does not necessarily reflect the exact nature of different fires. For example, peat fires in tropics are mainly due to intentional drainage followed by burning to remove a (bogged) forest (thus anthropogenic, e.g., Marlier et al., 2015), while in northern high-latitude regions peatland fires might be due to drought (thus natural, e.g. Turetsky et al., 2011)."

Pg 9028, Lines 23-24: Another note to include explanation of how some deforestation fires

are captured by the model.

[Response] This is now included in the updated section 2.3 and the readers are thus referred to that section.

Pg 9031, Lines 4-15: This is an excellent point and really adds nicely to the overall analysis. It could be even better with a sentence added that connects the idea laid out in the first sentence of the paragraph (emission variability driven by forest fires, burned area variability driven by grassland/savannah fires) to the difference between the model and GFED.

[Response] The following sentence is added at the end of this paragraph to link the difference again back to the phenomenon pointed out in the first sentence: "because emissions are dominated by litter burning (from grassland, savanna and forest) and are less driven by forest fires that involve large amount of live biomass burning."

Pg 9033, Lines 1-3: The difference in fuel consumption between the model and GFED in tropical grasses/savannah especially is very large, as pointed out in this text and shown in figure 5. Could the authors provide some insight at this point in the text into why the numbers may be so different for these fires (i.e. combustion completeness)?Maybe something as simple as noting that the differences in combustion completeness are driving this discrepancy and they will be discussed in the next section.

[Response] We inserted the following sentence at the end of the paragraph: "The simulated higher fuel consumption in tropical savannas and woodland savannas might be due to a combination of overestimated fuel load and combustion completeness, which is discussed in more detail in section 3.2.4. Further, we acknowledge the fact that ORCHIDEE can have grass and tree PFTs coexisting on the same grid point, but does not describe woody savannas or miombo forests where grass and trees compete locally for water, light and nutrients and could have lower fuel consumptions due to the presence of fire resistant tree species (Hoffmann et al., 2012)".

Pg 9035, Lines 1-3: The van Leeuwen et al. (2014) combustion completeness values might not change the global emissions by much, but maybe they improved the spatial distribution of fuel consumption as compared to the GFED? If so, this could warrant anew figure, or a new panel in Figure 5 showing the difference.

[Response] We are not able to give the spatial distribution of fuel consumption by using combustion completeness (CC) from van Leeuwen et al. (2014) because on Page 9035, Lines 1-3 what we did is a simple adjustment of emissions by using ratios of applied CCs against updated CCs in Leeuwen et al. (2014) rather than a new simulation. We think a new simulation with updated CCs in Leeuwen et al. (2014) could improve the spatial agreement with GFED data in fuel consumption but might not be as much as expected, because fuel load needs also to be accurately calibrated, and simultaneous change in CCs in forest and grassland might partly oppose each other to lower the change, and because van Leeuwen et al. (2014) is in fact not used in GFED data either. However, van Leeuwen et al. (2014) reported for some biomes the CCs for woody litter with different diameter size, which resembles the fuel category used in our model, and this gives a very promising way to include this data in our model in the future. Finally, one has to note that the CCs in GFED data are also derived by scaling the lower and higher boundaries using an estimate for potential evapotranspiration, which is a source of uncertainty. GFED emissions estimates use extensively observed burned area and other datasets (such as tree cover distribution) and a sophisticated scheme to derive emissions, but it is not a fully observation-based data set. Some independent (top-down) approach would rather be needed to constrain the bottom-up emissions estimates.

Section 3.3.1: The figure is really nice, a great concept. Are the data used from the model? If so, would it make more sense to use the full century of model output? This might change the look of the high latitude regions which have longer fire return intervals. I had difficulty understanding parts of this section – Line 12 should read that agricultural harvest PLUS heterotrophic respiration account for 91% off NPP, correct? And I might be missing something but 100% minus RH plus CH (91.0%), minus FE(3.4%) leaves 5.6% for NBP instead of 5.2% as written in the text.

[Response] All data used in Figure 8 are from model output. We have checked the same figure for the 1901-2012 average. The spatial pattern does not change significantly since average annual emission and NPP were used in Figure 8, thus the fire return interval has little influence on the spatial pattern (because mean annual burned fraction is often regarded as the inverse of fire return interval). We put the figure for the 1901-2012 average, and its difference from 2003-2012 average into supplement material as Fig. S6.

We regret the confusion in terms of NPP allocation in component fluxes. As mentioned in section 2.3, there is a remaining positive NBP of 0.19 Pg C yr^{-1} at the end of spin-up and this is subtracted from global simulated NBP when doing analysis on global scale. So if we take this part into account, then the NBP takes up 5.5% of simulated NPP. The percentage of RH plus CH should be 91.1% if the decimal errors in calculation are adjusted. In this way, the different component fluxes add up to 100% of simulated NPP. This is now clarified in the updated texts.

Pg 9036, Line 7: What measure of variability or uncertainty is the plus/minus representing here?

[Response] The standard deviation of SR_{fire} is used.

Pg 9036, Line 14: Is soil organic matter considered available fuel for model fires? This could also be addressed in the brief SPITFIRE description in Section 2.

[Response] We added in section 2 two paragraphs describing briefly the processes of SPITFIRE. The soil organic litter (more often used in boreal regions to refer to accumulated organic matter during intervals between fire disturbances) is treated as "normal litter" in ORCHIDEE and is available for burning.

Pg 9036, Line 19: This is where I thought that discussion of the model treatment of fire-caused mortality of vegetation would be helpful. This role of fires, converting live vegetation C to litter C, should be mentioned here when explaining how fires are analogous to respiration.

[Response] According to the review comments, we briefly described how fire-caused tree mortality is simulated in the model in the updated section 2. There are two basic roles of fires in our model. The first is that fires consume surface litter carbon and part of live biomass carbon and release them into the atmosphere. This role is analogous to heterotrophic respiration and relates to the "fire respiration partial compensation", and is our focus here (in Line 19). This is not to be confused with the second role, that live tree biomass that is killed but not completely combusted by fire will turn into litter. Furthermore, we modified the Line 19 in the revised manuscript to reflect that, the role of fire is "partial" respiration compensation, i.e., fires reduce carbon sink for both low and high fire years, but larger sink reduction occurs for high fire years (as pointed out by the reviewer in previous comments).

Pg 9037, Lines 14-16: This contention would carry more weight if half of the lowest SRfire years were not also after 1970 (after 1980 in this case). Also, precipitation patterns also have a role in determining the high/low years (as the authors note in the following paragraph) and the uncertainty in these fields in the climate data used for atmospheric forcing is high for the first half of the 20th century. I recommend removing this sentence. Also Hartmann et al. (2013) is not listed in the references.
[Response] Considering the uncertainty in the climate data in the first half of the 20th century as pointed out by the reviewer, we removed this sentence and the accompanying reference.

Pg 9038, Lines 12-17: This is stated very nicely. In some ways the SRfire analysis is better without the deforestation fires since it provides a nice wildfire-only baseline to compare anthropogenic impacts against.
[Response] Thanks for the positive comment.

Section 3.3.4: It is a good idea to compare the results of this study to a previous study, Li et al. (2014) in this case. To my mind this discussion can be greatly reduced in scope, maybe even down to just a few sentences. The important parts to note are the big difference in the sink reduction predicted in the two studies, and the major differences in the studies that could lead to this discrepancy.
[Response] We feel like this amount of text is needed for a decent comparison with Li et al. (2014), given that their paper is the only published work addressing a similar issue as ours when we prepared the manuscript.

Table 1: It would be great to have global totals for emissions and burned area included in this table.
[Response] This information is provided as the last row of Table 1.

Figure 6, caption: It was unclear to me what was meant by "based on grid cell area" here. This seems inconsistent with the units given which are per meter squared.
[Response] We have changed the caption to "..., based on the whole grid cell area included both burned and unburned parts." This metric allows easy comparison among different datasets because simply by multiplying the grid cell land area one could get the amount of emissions.

Technical changes:
Pg 9022, Line 11: Delete "issues of what"
[Response] Done.

Pg 9025, Line 7: Change to “A ratio of simulated GPP to MTE-GPP was: : :”

[Response] Done.

Pg 9032, Line 1: “possibly” might be better word choice than “probably” here.

[Response] Done.

Pg 9034, Lines 7-8: This sentence could be stronger if “indicating that the simulated fuel load might be comparable to GFED3.1 data” was deleted.

[Response] We decided not to remove this part, as we cannot fully exclude the error in simulated fuel load. Comparable NPP does not necessarily lead to comparable fuel load because the carbon turnover processes might be different in two models, thus leading to different sizes in litter pool, which is a major fuel source for fire. But as the fuel load data is not provided in Table 4 of van der Werf et al. (2010), we are not able to do the comparison in terms of fuel load as the case of NPP and combustion completeness.

Pg 9037, Lines 11-13: Note that the SRfire numbers used here are global.

[Response] Done.

Pg 9037, Line 16: Change “The SRfire: : :” to “The average SRfire: : :”

[Response] Done.

Pg 9038, Line 23: A couple word choice recommendations – change “limit” to “average”and “accelerated” to “increased”.

[Response] Kelly et al., 2013 as cited used sediment records to examine historical fire frequency, so ‘limit’ corresponds to ‘range’ here which does not give the exact quantitative measurement. Therefore the use of ‘limit’ makes more sense for us. The second recommendation is adopted.

Pg 9039, Line 13: Change “by the two” to “from the two”

[Response] Done.

Pg 9040, Line 13: Change “NPP by fire” to “NPP lost to fire”

[Response] This is an indeed a better way of expressing; change was made.

Pg 9041, Line 17: Is this Table 1 “in” Archibald et al., 2013?

[Response] We changed it to "Table 1 in Archibald et al., 2013"

Table 1 caption: Fix “GEFD”

[Response] Done.

Figure 8 caption: Delete “returned to the atmosphere”

[Response] Done.

Interactive comment on “Modelling the role of fires in the terrestrial carbon balance by incorporating SPITFIRE into the global vegetation model ORCHIDEE – Part 2: Carbon emissions and the role of fires in the global carbon balance” by C. Yue et al.

Anonymous Referee #2
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[1] Yue and colleagues investigated the spatial and temporal patterns of global fire carbon emissions during 1901-2012 using the ORCHIDEE model. The goal of this work was to evaluate regional characteristics of fire activity (Pyromes, GFED regions) and estimate the net effects of fire activity for global carbon cycling. Model simulations with and without fires considered the potential impacts of fire activity on vegetation carbon storage over a range of time scales. The sequence of analyses stem from simulations of contemporary fire activity, using the GFED3.1 dataset of burned area observations and modeled fire emissions to characterize ORCHIDEE model results. Unfortunately, these comparisons highlight gross disparities between ORCHIDEE results and observations. The inability to reproduce a reasonable pattern of burned area and fire emissions (1997-2010) precludes a more detailed analysis of the century-scale patterns of fire activity and NBP. At these longer time scales, the analysis likely propagates model biases, rather than elucidating carbon cycle dynamics over time scales relevant for carbon cycling.

[Response] We greatly appreciate the efforts of the reviewer who provided us with some very interesting comments and suggestions. Please find our detailed response below each of the original comments. To facilitate the reading, we marked all modified text in the updated manuscript in red.

We explained in section 2.2 and 3.1 that the productivity has been re-calibrated for the model and this led to underestimated burned area compared with prior-calibration. As we focus on fire emissions and their role in carbon cycling for the past century, the precise representation of burned area in the model is considered less important than that of emissions. Figure 5 and Figure 6 shows that the simulated spatial pattern of fire emissions is quite similar with that of the GFED3.1 estimates. In particular, Figure 6 shows the carbon emissions per grid cell area, a metric directly relevant to emissions quantification.

The focus of the current study is the role of fire in terrestrial carbon cycling compared with a model simulation without fire linked to long-term variation of fire carbon emissions. Model evaluation was conducted for a short recent period of 1997-2009 by using GFED3 data. Over the 20th century, we showed in Yue et al. (2014) that the ORCHIDEE-SPITFIRE model can broadly capture the decadal variation of global burned area compared with the historical reconstruction data by Mouillot and Field (2005), the only available global historical reconstruction to our knowledge. In the current study, the simulated vegetation productivity has been re-calibrated and this leads to changes in the magnitude of simulated burned area compared with Yue et al. (2014), but the interannual variability in both burned area and fire emissions remains conserved (correlation coefficient for fire carbon emissions as 0.97 between the two simulations before and after calibration). Given the encouraging model performance when being compared with Mouillot and Field (2005) historical data, we remain reasonably confident on the model results for the past century. Note also that in the FireON simulation, after accounting for fire carbon emissions, simulated NBP (i.e. carbon sink) has a rather reasonably good correlation with the residual land sink (correlation coefficient = 0.59, more details see section 2.3.2). It is rather unlikely that this would have been achieved if simulated historical fire variation had diverged in an unrealistic way from the truth.

However, we do recognize that over the model evaluation period of 1997-2009, despite the quite close total fire emissions to GFED3.1 data, the simulated interannual variability in emissions is underestimated (Figure 3). If this underestimation persists over the historical period, the difference in fire-induced sink reduction (SR_{fire}) between high and low fire years will be underestimated. The estimated mean annual SR_{fire} remains reliable within the limit of our model capacity and simulation framework, because our estimated total fire emissions are close to GFED3.1 data and other modeling studies (see the results from a GFED3.1 burned area forced model simulation in the response to #3 comment).

Finally, some of the limitations in our models are in fact shared by most of the global dynamic vegetation models with fire modules. For example, Li et al. (2013) examined spatial correlation between their simulated grid-cell-area-based fire emissions and those of GFED3.1 data for 1997-2004, and the correlation coefficient ranged from 0.32 to 0.53. The spatial correlation between our fire emissions and GFED3.1 data for 1997-2009 (re-gridded at 2-degree, comparable spatial resolution with Li et al. 2013) is 0.29, slightly lower than Li et al. (2013). If we take a look at other SPITFIRE-based fire models, either no report is made on the comparison on spatial distribution of fire emissions (e.g., Kelley et al., 2014; Pfeiffer et al., 2013; Prentice et al., 2011), or gross disagreements with GFED data exist (e.g., Figure 5 in Lasslop et al., 2014). The same also applies to the temporal pattern of simulated fire emissions. None of the above-mentioned SPITFIRE-based fire modeling studies compared the temporal pattern between simulated fire carbon emissions and GFED3.1 estimates. The model of Yang et al. (2014) simulates fire occurrence and emissions in a different approach from SPITFIRE. They compared annual variability of simulated burned area with GFED3 data for 1997-2007, and the 1998 fire anomaly has been underestimated as well. It seems that the underestimation of 1997-1998 fire emissions anomaly is a common feature of above-mentioned fire models except in Li et al., (2013), where peat burning is included based a prescribed peat distribution map and fixed peatland fire consumption rates. Indeed, a large fraction of 1997-1998 global fire emissions anomaly is contributed by anthropogenic burning in peatland and deforestation fires in tropical Asia and America (Field et al., 2009; Page et al., 2002; van der Werf et al., 2004, 2010). It's unlikely for fire models without a dedicated peatland fire module to be able to capture this anomaly.

Even though our model is far from being 'perfect', the detailed evaluation as presented in Yue et al. (2014), the comparable spatial emission pattern and global total fire emissions with GFED, and the reasonable representation of residual carbon sink estimates, give us confidence and therefore we disagree with the reviewer that some of our model deficiencies preclude the analyses we presented. We acknowledge that model limitation does exist, such as that the underestimation of temporal variability in fire emissions compared with GFED3.1 which is a quasi inventory-based data set. However, we argue that our model also has advantages such as that it could be used to examine long-term historical (as we presented) and future fire activities which inventory-based approach cannot handle simply because of lack of observation data. Based on the detailed model calibrations, we are cautiously confident that our modeling study could provide some meaning insights for the role of fire in the historical carbon cycling.

The likely influence of underestimated interannual variability in fire emissions on the simulated role of fire in the carbon cycling is discussed in section 3.3.3 in the updated manuscript.

[2] Comparisons between ORCHIDEE and GFED3.1 for the spatial and temporal patterns of global fire activity are puzzling (Table 1, and Figures 2-7). Not getting Africa right is a problem, or even wrong for the right reasons, since this is the region with the most consistent patterns of burned area (see Andela& van der Werf, 2014; also van der Werf et al., 2010 and Giglio et al., 2013). Burned area estimates for

Africa are only 27-46% of observations, yet fuel consumption estimates are very high (3-4x). These differences point to significant limitations of the current model setup to reproduce fire activity and fire emissions; NHAF and SHAF are dominated by savanna and woodland fire types, two of the major fire types represented in this version of ORCHIDEE. Australia follows the same pattern («burned area, » fuel consumption). Temporal variability in global burned area and fire emissions is also underrepresented in the model results, with little interannual variability in fire emissions at the regional scale.

[Response] The inclusion of SPITFIRE into the global land surface model ORCHIDEE represents a significant structural change. In Table 1 we compared in a very detailed manner the fire emissions between model simulation and GFED3.1 data and all relevant components to derive fire emissions, in order to identify model errors for future improvement. As we explained in the response to the comment above, burned area here is not the central focus but the comparable total global fire emissions with GFED3.1 is essential to have reliable estimates of NBP and fire-induced sink reduction. Figure 2-4 are mainly for informative purposes. In Figure 5 and 6 the comparisons between simulated fire emissions and GFED3.1 data are reasonable. Figure 7 further complements Table 1 to attribute carbon emission error to burned area and fuel consumption on a latitudinal gradient. So the table and all figures focus on the evaluation of fire emissions, error attribution and implications for future model improvement. We hope that they provide useful information for model calibration in the context of the research objective.

We agree with the reviewer that there is disagreement between model and GFED3.1 data in the simulated burned area and fuel consumption in savanna and woodland fires in Africa and Australia. Comparable fire emission per grid cell area with GFED3.1 estimates can only be made when the errors compensate. We acknowledged and discussed these findings in sections 3.2.3 and 3.2.4. The total fire carbon emissions in Africa and Australia are comparable between model and GFED3.1 because an overestimation in NHAF is partly compensated by underestimation in SHAF. As the total amount of emissions is constrained, we think our model application is valid despite the limitations in reproducing the exact regional pattern of fire activities and emissions. At the same time, we noticed that not getting Africa right is a shared problem of some other models (see Figure 4 in Lasslop et al., 2014; Figure 2 in Prentice et al., 2011; Fig.12 in Pfeiffer et al., 2013). Some disagreements in our results could be linked to a lack of deforestation and agricultural fires and to a too simple parameterization of human ignitions. The disagreements between model simulation and GFED3.1 for land cover types like savanna and woodland could be related with the fundamental approach used to simulate fire processes. For example, given the same fraction of grassland versus tree distribution in a grid cell, evenly-distributed woody vegetation with grass cover between trees would lead to very different fuel characteristics compared to a forest fraction being separated from grasslands. Therefore the fire spread rate would be lower in the first case than the second one. However, this difference cannot be properly represented in the current model setup that represents abstract amount of tree versus grassland fractions. Most DGVMs don't simulate trees-grass-fires interactions at ecosystem scale (Li et al., 2013; Lasslop et al., 2014; Pfeiffer et al., 2013; Yang et al., 2014). We discussed in detail in Yue et al. (2014) the challenges in simulating mechanistic fire processes in our model but most of these are also shared by other process-based global fire models. To completely solve this issue, more careful and dedicated calibration study needs to be done on regional scale which is currently beyond our scope here. Please also note that we're not using regional specific parameters in the ignition equations, so the first step for improvement might be to have regional parameters before going more deeply in fire processes.

We acknowledged in the response to the #1 comment that the interannual variability in fire emissions is underestimated and the potential influence on our conclusions is now discussed in section 3.3.3. One of the reasons for this underestimation could be related to the different vegetation types that are represented in the model. For example, fires in temperate forest could lead to complete regeneration of new forest patches as a small fraction of a 0.5-degree simulation grid cell. However in the model, this mortality effect is dissipated over the whole grid cell because forest cohorts of different ages after fire are not explicitly represented, thus potentially leading to underestimated damaging effect on trees and subsequent faster forest regrowth. Additional model developments and simulations are needed to confirm the existence of this influence and examine how big it could be on fire activities and emissions.

[3] The validity of the sink reduction (SR) estimates fundamentally depends on getting burned area in the right amounts in the right biomes. Since tropical fires are underestimated, but total emissions are even higher than contemporary estimates from GFED3.1, does this lead to a biased estimate of the SR? Similarly, underestimating interannual variability of fire activity in ORCHIDEE could dampen distinct phases of higher or lower fire activity, with important implications for NBP calculations and contemporary fire risk. Since the model is unable to capture regional and interannual variability in burned area and fire emissions, deeper model interrogation of NBP and SR seems risky, at best (Section 3.3).

[Response] Again, the validity of our study depends on getting the total fire emissions right but not exactly the right burned area. Notably, the total fire emissions for savanna and woodland vegetation in Africa and Australia are in agreement with GFED3.1 data at continental scale. To address precisely the question of the reviewer about the uncertainty of calculated SR_{fire} caused by simulated burned area in the model, we re-run the model for the period of 1997-2009, but with the burned area being externally forced by GFED3 observation data.

When the external burned area data is forced into the model, the SPITFIRE module is operated on a monthly time step, to reconcile the inconsistency of simulated date of burning and reported date of burning. The processes for burned area simulation in the module are simply de-activated, and the input burned area is used directly to calculate the emissions. Emissions from tree live crown scorching and fire-caused tree mortality are not included, because in case of forced burned area, the fire spread rate, fire intensity, tree mortality and relevant variables are not simulated. However, the combustion of live grass and dead fuels on the ground are included, which account for the majority of the total emissions. In terms of the combustion completeness, regional specific values as reported in the GFED3.1 database (as reported in Table 4 in van der Werf et al., 2010 for the 14 regions) are used in the model as constant combustion completeness.

The simulated fire carbon emissions from original ORCHIDEE simulation, ORCHIDEE simulation forced by GFED3 burned area (BA), and fire carbon emissions reported by GFED3.1 data are shown in Figure 1. The agreement in the interannual variability of fire carbon emission between the model and GFED3.1 data improves when the model is forced by GFED3.1 BA data, though not exactly identical. The mean annual emissions for 1997-2009 in the forced BA simulation are 1.8 Pg C yr^{-1}, slightly lower than the 2.0 Pg C yr^{-1} given by GFED3.1 data and the 2.1 Pg C yr^{-1}given by the original simulation. As simulated BA-forced annual emissions deviate from the original simulation, the annual time series of SR_{fire} in the forced simulation also differs from the original simulation. The mean SR_{fire} over 1997-2009 given by the forced simulation is 0.39 Pg C yr^{-1}, slightly lower than the 0.36 Pg C yr^{-1} given by the original simulation. The two estimates are very close to each other, indicating that there is no large bias on SR_{fire} induced by the systematic underestimation of BA. This has been explained in section 3.3.3 the revised manuscript.

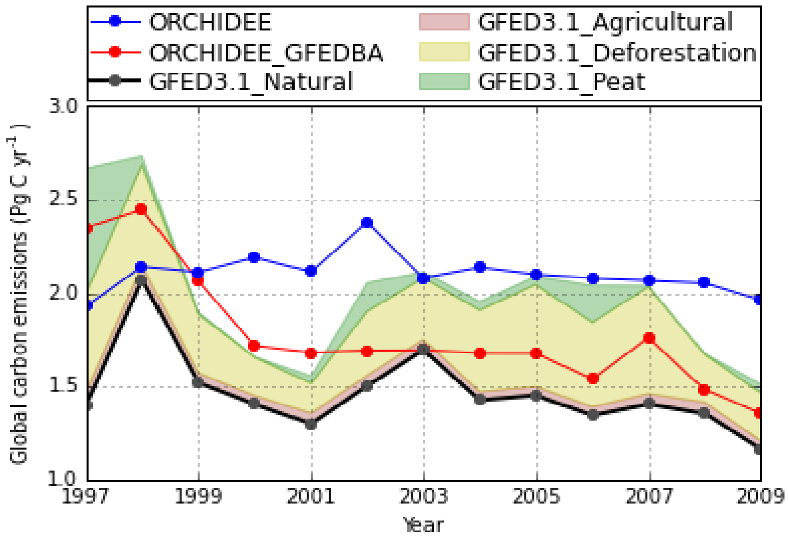

Figure 1 Fire carbon emissions from the original ORCHIDEE simulation (in blue), ORCHIDEE forced by GFED3.1 burned area data (in red), and different GFED3.1 emissions components.

[4] Additional comments on model setup: Static land cover assumption: Estimates of contemporary land cover may be suitable for decadal simulations. However, over century time scales, landscape connectivity and biome distributions can differ substantially. How might land cover differences alter the time series of burned area?

[Response] When we use a static land cover, there are two factors which we do not include in our simulation. The first is natural vegetation change (e.g., biome distribution change as pointed out by the reviewer) induced by environmental changes that are usually simulated by the dynamic vegetation component by DGVM models. The second is the land cover transformation and land characteristics change (such as landscape connectivity as pointed by the reviewer) that are imposed by humans. We showed some results for southern Africa by coupling SPITFIRE with the dynamic vegetation module of ORCHIDEE in Yue et al. (2014) (see discussions in section 4.2.4 and Figure S12 in the supplement in that paper). As the model calibration for fire-vegetation-climate feedbacks is not yet satisfactory (which we believe is the case as well for most fire DGVMs), we chose to not include this component in our simulation as it bring uncertainties that were not simple to interpret and attribute to model structural errors.

Very few studies quantified the burned area contributed by anthropogenic land use and land cover change and their net effect on the temporal trend and variability of burned area. Kloster et al., (2010) estimated that deforestation and wood harvest for 1850-1990 together reduced fire carbon emissions in the 1990s by 16% (433 Tg C/year), however the net amount of burned area might be small (assuming a 3000gC m^{-2} of carbon consumption in deforestation fire, the net amount of burned area is 14.4 Mha, or 4% of annual global burned area by GFED3 data). We indicated in section 2.3 that our model captures 92% of GFED3 tropical (20^{o}S–20^{o}N) fire emissions, excluding agricultural and peat fires but including deforestation fires in GFED3. So part of deforestation fire emissions are included in our model but the corresponding burned area is not explicitly represented and separated. Thus we limit our analysis scope more to “naturally occurring vegetation fires” as stated on line 14, Page 9022. We agree with the reviewer that the landscape connectivity as transformed by human activities does influence fires such as fire propagation and potential fire size. However, this fragmentation effect is not included in our model (and almost all other global fire models). To our knowledge no global targeted study tried to examine this issue so far. On the other hand, as the total amount of fire emissions from our simulation is constrained by GFED3.1 data which is build on top of observed burned area (which takes into account the land fragmentation effect), our estimation of global total NBP and SR_{fire} are expected to be credible.

[5] Ignitions: Why was the lightning data cycled, especially for a 5yr period with a strong ENSO event, rather than linking lightning to climate data?
[Response] To our knowledge the LIS/OTD lightning data used in our simulation is the only freely available gridded lightning observation data covering the whole globe to date. We agree with the reviewer that lightning activities are linked with climate state and it should be more reasonable to use temporally variable lightning data rather than cycling the same data. To have varying lightning input, we thus need to calculate lightning flashes from some climate variables. We tried to follow the approach proposed by Pfeiffer et al., (2013) to derive temporally varying lightning data from the convective available potential energy (CPAE) provided by he 20th Century Reanalysis Project (http://portal.nersc.gov/project/20C_Reanalysis/) and applied in our model, however no significant improvement with observed burned area data was found (see more details, please refer to section 4.2.1 Yue et al., 2014 and the accompanying supplement). Krause et al. (2014) explored the impact of changing lightning activities due to climate change on burned area by estimating lightning flashes from convective cloud top height as simulated by coupled MPI earth system model. They found a -0.2% to 3.3% change of global burned area for preindustrial and end-of-21stcentury RCP85 lightning activities, both being compared with present day burned area. Despite a lot of uncertainties, the overall change in burned area caused by lightning change could be small on the global scale. This is even more the case when considering the dominant human ignition sources in most of the continents, even in some boreal regions (e.g., see Mollicone et al., 2006 on the causes on Russian boreal fires). As most of our analysis relies on a global constrained fire emissions, and taking into account further uncertainties in the reconstructed lightning data, we see little benefit by making the extra efforts to include varying lightning input into our simulation.

[6] Format: The first paragraph of Section 2.2 seems out of place. Comparisons with burned area were done in Yue et al., 2014 and could be referenced, rather than repeated.
[Response] As the vegetation productivity was re-calibrated in our simulation, the simulated burned area changed against to that in Yue et al., (2014). We therefore briefly discussed this change in section 2.2 and also in section 3.1.

[7] Mixture of methods and results in Section 2.3. (e.g., 9026, lines 4-15).
[Response] There is rather no strict clear line between what should belong to the methods and what fits the results. For lines 4-15 on Page 9026, we compared the simulated fire emissions with GFED3.1 data for tropical regions, by separating the emissions into difference sources, notably sources that are explicitly included in our model and those not included. By presenting these in the methods, we think it follows the logic of model introduction regarding what fires are included in our model and not included. We also tried to give an idea how much deforestation fire emissions are implicitly included in our model, as our model could capture part of the "climate windows" that regulate deforestation fires. These are supposed to provide a better context to understand the results that follow. Therefore we think that it is appropriate to present these findings in the methods section.

References:

Field, R. D., Werf, G. R. van der and Shen, S. S. P.: Human amplification of drought-induced biomass burning in Indonesia since 1960, Nat. Geosci., 2(3), 185–188, doi:10.1038/ngeo443, 2009.
Kelley, D. I., Harrison, S. P. and Prentice, I. C.: Improved simulation of fire–vegetation interactions in the Land surface Processes and eXchanges dynamic global vegetation model (LPX-Mv1), Geosci Model Dev, 7(5), 2411–2433, doi:10.5194/gmd-7-2411-2014, 2014.
Kloster, S., Mahowald, N. M., Randerson, J. T., Thornton, P. E., Hoffman, F. M., Levis, S., Lawrence, P. J., Feddema, J. J., Oleson, K. W. and Lawrence, D. M.: Fire dynamics during the 20th century simulated by the Community Land Model, Biogeosciences, 7(6), 1877–1902, doi:10.5194/bg-7-1877-2010, 2010.
Krause, A., Kloster, S., Wilkenskjeld, S. and Paeth, H.: The sensitivity of global wildfires to simulated past, present, and future lightning frequency, J. Geophys. Res. Biogeosciences, 119(3), 312–322, doi:10.1002/2013JG002502, 2014.
Lasslop, G., Thonicke, K. and Kloster, S.: SPITFIRE within the MPI Earth system model: Model development and evaluation, J. Adv. Model. Earth Syst., (06), 740–755, doi:10.1002/2013MS000284, 2014.
Li, F., Levis, S. and Ward, D. S.: Quantifying the role of fire in the Earth system – Part 1: Improved global fire modeling in the Community Earth System Model (CESM1), Biogeosciences, 10(4), 2293–2314, doi:10.5194/bg-10-2293-2013, 2013.
Mollicone, D., Eva, H. D. and Achard, F.: Ecology: Human role in Russian wild fires, Nature, 440(7083), 436–437, doi:10.1038/440436a, 2006.
Mouillot, F. and Field, C. B.: Fire history and the global carbon budget: a 1 degrees x 1 degrees fire history reconstruction for the 20th century, Glob. Change Biol., 11, 398–420, doi:10.1111/j.1365-2486.2005.00920.x, 2005.
Page, S. E., Siegert, F., Rieley, J. O., Boehm, H.-D. V., Jaya, A. and Limin, S.: The amount of carbon released from peat and forest fires in Indonesia during 1997, Nature, 420(6911), 61–65, doi:10.1038/nature01131, 2002.
Pfeiffer, M., Spessa, A. and Kaplan, J. O.: A model for global biomass burning in preindustrial time: LPJ-LMfire (v1.0), Geosci Model Dev, 6(3), 643–685, doi:10.5194/gmd-6-643-2013, 2013.
Prentice, I. C., Kelley, D. I., Foster, P. N., Friedlingstein, P., Harrison, S. P. and Bartlein, P. J.: Modeling fire and the terrestrial carbon balance, Glob. Biogeochem. Cycles, 25, GB3005, doi:201110.1029/2010GB003906, 2011.
Van der Werf, G. R., Randerson, J. T., Collatz, G. J., Giglio, L., Kasibhatla, P. S., Arellano, A. F., Olsen, S. C. and Kasischke, E. S.: Continental-Scale Partitioning of Fire Emissions During the 1997 to 2001 El Niño/La Niña Period, Science, 303(5654), 73–76, doi:10.1126/science.1090753, 2004.
Van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y. and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), Atmos Chem Phys, 10(23), 11707–11735, doi:10.5194/acp-10-11707-2010, 2010.
Yang, J., Tian, H., Tao, B., Ren, W., Kush, J., Liu, Y. and Wang, Y.: Spatial and temporal patterns of global burned area in response to anthropogenic and environmental factors: Reconstructing global fire history for the 20th and early 21st centuries, J. Geophys. Res. Biogeosciences, 249–263, doi:10.1002/2013JG002532, 2014.
Yue, C., Ciais, P., Cadule, P., Thonicke, K., Archibald, S., Poulter, B., Hao, W. M., Hantson, S., Mouillot, F., Friedlingstein, P., Maignan, F. and Viovy, N.: Modelling the role of fires in the terrestrial carbon balance by incorporating SPITFIRE into the global vegetation model ORCHIDEE – Part 1: simulating historical global burned area and fire regimes, Geosci Model Dev, 7(6), 2747–2767, doi:10.5194/gmd-7-2747-2014, 2014.

Title:

Modelling the role of fires in the terrestrial carbon balance by incorporating SPITFIRE into the global vegetation model ORCHIDEE – Part 2: carbon emissions and the role of fires in the global carbon balance

Running title: Modelling the role of fires in the global carbon balance

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Abstract

Carbon dioxide emissions from wild and anthropogenic fires return the carbon absorbed by plants to the atmosphere, and decrease the sequestration of carbon by land ecosystems. Future climate warming will likely increase the frequency of fire-triggering drought, so that the future terrestrial carbon uptake will depend on how fires respond to altered climate variation. In this study, we modelled the role of fires in the global terrestrial carbon balance for 1901–2012, using the global vegetation model ORCHIDEE equipped with the SPITFIRE model. We conducted two simulations with and without the fire module being activated, using a static land cover. The simulated global fire carbon emissions for 1997–2009 are 2.1 Pg C yr^{-1}, which is close to the 2.0 Pg C yr^{-1} as estimated by GFED3.1. The simulated land carbon uptake after accounting for emissions for 2003–2012 is 3.1 Pg C yr^{-1}, which is within the uncertainty of the residual carbon sink estimation (2.8 +/- 0.8 Pg C yr^{-1}). Fires are found to reduce the terrestrial carbon uptake by 0.32 Pg C yr^{-1} over 1901–2012, or 20% of the total carbon sink in a world without fire. The fire-induced land sink reduction (SR_{fire}) is significantly correlated with climate variability, with larger sink reduction occurring in warm and dry years, in particular during El Niño events. Our results

suggest a "fire respiration partial compensation". During the ten lowest SR_{fire} years (SR_{fire} = 0.17 Pg C yr^{-1}), fires mainly compensate for the heterotrophic respiration that would occur in a world without fire. By contrast, during the ten highest SR_{fire} fire years (SR_{fire} = 0.49 Pg C yr^{-1}), fire emissions exceed far their "respiration partial compensation" and create a larger reduction in terrestrial carbon uptake. Our findings have important implications for the future role of fires in the terrestrial carbon balance, because the capacity of terrestrial ecosystems to sequester carbon will be diminished by future climate change characterized by increased frequency of droughts and extreme El Niño events.

1 Introduction

Vegetation fires contribute significantly to the interannual variability (IAV) of atmospheric CO_2 concentration. Deforestation and peat fires emit carbon that is not offset by rapid vegetation regrowth, and thus contribute to a net increase of atmospheric CO_2 (Bowman et al., 2009; Langenfelds et al., 2002; Schimel and Baker, 2002; van der Werf et al., 2009). Besides the direct effect of fires in reducing the capacity of terrestrial ecosystems to sequester carbon, other greenhouse gases (e.g., CH_4, N_2O), ozone precursors, and aerosols emitted by fires are a net source of radiative forcing (Podgorny et al., 2003; Tosca et al., 2010; Ward et al., 2012). Finally, fires can also impact climate by changing the land surface properties, such as vegetation structure and albedo (Beck et al., 2011; Jin et al., 2012), as well as the energy partitioning (Liu and Randerson, 2008; Rocha and Shaver, 2011). Changes in temperature and precipitation patterns, in particular drought frequency and severity, also influence fire regimes and their emissions (Balshi et al., 2009; Kloster et al., 2012; Westerling et al., 2011) causing complex fire-vegetation-climate interactions.

The estimation of global carbon emissions from fires was pioneered by Seiler and Crutzen (1980), who used available literature data of field experiments to assess important fire parameters like area burned, fuel load and the combustion completeness. More recently, large-scale spatially explicit estimation of fire carbon emissions has been aided by satellite-derived burned area and active fire counts (Giglio et al., 2010; Roy et al., 2008; Tansey et al., 2008), as well as vegetation models in which burned area is either prescribed (Randerson et al., 2012; van der Werf et al., 2006, 2010) or simulated with a prognostic fire model (Kloster et al., 2010; Li et al., 2013; Prentice et al., 2011; Thonicke et al., 2010). Several recent estimates have converged to give annual fire carbon emissions of ~2 Pg C yr^{-1}, as pointed out by Li et al. (2014). Van der Werf et al. (2006) showed that the IAV of global fire carbon emissions is decoupled from the variation in burned area, mainly due to the disproportionate contribution to global emissions by fires with a large fuel consumption (forest fire, deforestation fire and peat fire). Prentice et al. (2011) examined how burned area in tropical and subtropical regions is influenced by the El Niño Southern Oscillation (ENSO) climate variability, and quantified the contribution of fire emission anomaly to the anomaly of land sink as diagnosed by atmospheric inversions. However, it is only recently that Li et al. (2014) have simultaneously constrained the simulated fire carbon emissions and net biome production (NBP, i.e., the land carbon sink) in their absolute terms, employing a modelling approach. These modelled components of the carbon balance have rarely been reported simultaneously before. Li et al. (2014) also compared the difference in simulated NBP from two simulations with and without fires. However, the specific climatic driving factors for this fire-induced NBP difference have not been investigated. Given the profound perturbation of the climate system by human activities (Cai et al., 2014; Liu et al., 2013; Prudhomme et al., 2013) and with fire activities likely increase in the future (Flannigan et al., 2009; Kloster et al., 2012), it is therefore important to examine how fires and their contribution to the global carbon balance have responded to historical climate variations. This knowledge will give us insight into the likely impact of fires on the future land carbon balance.

Just as vegetation can be classified into biomes according to its climatic, morphological and physiological features, so fires occurring under different climate and vegetation patterns have distinctive features that allow them to be characterized by *fire regime*. Attributes of different fire regimes include the frequency, season, size, intensity and extent of fires (Gill and Allan, 2008). Trade-offs may exist between these different aspects of fire, e.g., ecosystems with frequent fires often have a long fire season but can hardly support high-intensity fires because of their low fuel load (Saito et al., 2014). Efforts have been made to further classify fires by examining co-occurring fire characteristics and relating these fire groups (named *pyromes*) to climatic, human and economic factors (Archibald et al., 2013; Chuvieco et al., 2008). Archibald et al. (2013) proposed an approach to divide fires into five pyromes, using the most extensive available global fire regime datasets including fire extent, fire season length, fire return interval, fire size and fire intensity. Though related to the biome distribution, pyromes are different from biomes. For example, the "Intermediate–Cool–Small" fire pyrome occurs throughout the globe, particular in regions of deforestation and agriculture, whereas the "Frequent–Intense–Large" fire pyrome is associated with tropical grassland-dominated systems. Different fire pyromes are suspected to also have impacts on the amount, seasonality and IAV of fire carbon emissions, and further consequences on the terrestrial carbon balance.

In a companion study (Yue et al., 2014), we incorporated the prognostic fire model SPITFIRE into the global vegetation model ORCHIDEE, and evaluated the modelled burned area and fire regimes during the 20th century using multiple observation datasets. In the present study, fire carbon emissions are simulated for 1901–2012, and the role of fires in the terrestrial carbon balance is investigated in relation to different climatic drivers and fire pyromes. Here we address what difference fires have made in the global terrestrial carbon balance, and how this difference is driven by large-scale climate variations, with a special focus on the naturally occurring vegetation fires. More specifically, the objectives of this study are to: (a) Benchmark the ORCHIDEE-SPITFIRE model in terms of simulated carbon emissions against GFED3.1 data, and identify model strengths and weaknesses. (b) Investigate the role of fires in the terrestrial carbon balance for 1901–2012 and the climatic factors driving its magnitude and temporal variation. This objective is tackled by conducting two simulations with and without fire occurrence. (c) Examine the characteristics of different fire regimes (as defined in Archibald et al., 2013) in terms of the role of fires in the terrestrial carbon balance. We hypothesize that more frequent and larger fires will have greater carbon consumption rates than infrequent and smaller ones, and consequently, the fire-induced carbon uptake reduction is larger in the former type of fires.

2 Data and methods

2.1 ORCHIDEE land surface model

ORCHIDEE is a global dynamic vegetation model that simulates the exchange of energy, water and carbon between the atmosphere and the land surface. It is the land surface model of the Earth system model IPSL-CM5 (Dufresne et al., 2013; Krinner et al., 2005). The processes and equations of the SPITFIRE fire model (Thonicke et al., 2010) were implemented in ORCHIDEE, with some modifications being described in Yue et al. (2014). There, the model was evaluated against different satellite observations for simulated burned areas and fire regimes.

The SPITFIRE module simulates burned area and fire consequences (e.g., emissions, plant mortality) in a mostly mechanistic way. The central underlying engine is the Rothermel's fire spread model (Rothermel, 1972; Pyne et al., 1996; Wilson, 1982), which links fire spread rate to fuel state, weather conditions and fire physics. Weather and fuel moisture conditions determine the time that a fire persists, which, combined with fire spread rate, yield an estimate of mean fire size. Ignition sources are scaled into fire numbers depending on weather conditions, with sources from both lightning and human activities being included. The daily burned area is thus derived as the product of fire number and mean fire size. Anthropogenic ignitions are estimated as a function of population density with the maximum ignition being obtained at ca. 16 ind km^{-2} (Venevsky et al. 2002, Thonicke et al. 2010). Anthropogenic ignitions are implicitly suppressed by human within the ignition equation, while lightning ignitions are not suppressed.

Fire carbon emissions follow a classical paradigm (Seiler and Crutzen, 1980) as the product of daily burned area, fuel load, and combustion completeness. Dead litter on the ground and live biomass from grasses and trees are available for burning. For live grass biomass and dead litter, combustion completeness is calculated as a function of fuel moisture state following the approach of Peterson and Ryan (1986). Tree crown live biomass consumption is simulated to depend on fire intensity and fire scorching height. Two factors are considered concerning fire-caused tree mortality: damage to tree crown because of crown scorching; and cambial damage linked with fire persistence time and tree bark resistance to fire. We refer the reader to Yue et al. (2014) and Thonicke et al. (2010) for a more detailed description of the fire module.

The simulation of combustion completeness (CC) for surface dead fuel was modified compared to the original scheme as presented by Thonicke et al. (2010). In SPITFIRE, the calculation of surface fuel CC follow Peterson and Ryan (1986), which allow CC to increase with decreasing fuel wetness and level out when the fuel wetness drops below some threshold (see Fig. 1 in Yue et al., 2014). During the model testing, it was found that simulated CCs were much higher than the recently compiled field observations for different biomes (van Leeuwen et al., 2014). We thus adjusted the maximum CC for fuel classes of 100 (with original maximum CC as 1.0) and 1000h (with original maximum CC as 0.8) to mean values provided by an earlier version of van Leeuwen et al. (2014) (Detmers, personal communication) which was available when preparing the current study. The categorization of fuels in terms of magnitude of hours describes the order of magnitude of time required to lose (or gain) 63% of the fuel moisture difference with the equilibrium moisture state under defined atmospheric conditions (Thonicke et al., 2010). The mean observational values were adopted as the maximum values in the model equations, because the simulated burned area is dominated with low fuel wetness, so that the simulated CC value is close to its maximum. However, we kept the original CC simulation scheme in the original SPITFIRE model for the convenience of future elaboration. According to the earlier version dataset of van Leeuwen et al. (2014), the biome-dependent maximum CC is 0.49 for tropical broadleaf evergreen and seasonal dry forests, 0.45 for temperate forests, 0.41 for boreal forests, and 0.85 for grasslands.

2.2 Model productivity calibration

As shown by Yue et al. (2014), the mean annual burned area on non-crop lands for 2001–2006 simulated to be 346 Mha yr^{-1} by ORCHIDEE. This falls within the range 287–384 Mha yr^{-1} from three global satellite-derived datasets (GLOBCARBON, L3JRC and GFED3.1), and is close to the 344 Mha yr^{-1} obtained in GFED3.1 when agricultural fires are excluded. The simulated global burned area on decadal time scale during the 20th century agrees moderately well with the historical reconstruction by Mouillot and Field (2005), corrected for regional mean bias using GFED3.1 for 1997–2000. However, one ORCHIDEE model shortcoming is that the terrestrial productivity is overestimated (as also revealed by Piao et al., 2013) possibly due to the absence of nutrient limitation, which leads to overestimated fire carbon emissions.

The simulated global gross primary productivity (GPP) by ORCHIDEE (version 1.9.6) as driven by CRUNCEP climate forcing data is 205 Pg C yr^{-1} for 1982–2010. This is much higher than the estimated 119 +/- 6 Pg C yr^{-1} by Jung et al. (2011), which was derived by interpolating eddy-covariance measurements over the globe using climate, remote-sensing fAPAR and a multiple tree regression ensemble algorithm (hereafter referred to as MTE-GPP). In order to correct for the positive bias of GPP, we use a simple approach to adjust the optimal carboxylation rates (V_{cmax}, in unit of μmol m^{-2} s^{-1}, see Eq.A2–A6 in Krinner et al., 2005) to match the simulated total GPP with the MTE-GPP reported for different biomes.

The default ORCHIDEE plant functional types (PFTs, excluding bare land) were grouped into five biomes: boreal forest, temperate forest, tropical forest, grassland and agricultural land.

The spatial extent of each biome was determined as the area where a corresponding ORCHIDEE PFT occupies more than 90% of a grid cell in the 0.5-degree MTE-GPP dataset. A ratio of simulated GPP to MTE-GPP was determined for each biome, and this ratio was used to adjust carboxylation rates (with the maximum potential rate of RuBP regeneration V_{jmax} being set to double of V_{cmax}). The original and calibrated carboxylation rates together with the biome-specific GPP ratios are given in Table S1. We emphasize that the approach employed here is an empirical and simple adjustment to calibrate ORCHIDEE productivity, but does not necessarily result in optimized carboxylation rates that agree with, for example, leaf-scale measurements (e.g., see discussion by Rogers, 2014).

2.3 Simulations and input datasets

To evaluate the role of fires in the global terrestrial carbon balance, two parallel simulations were conducted: fireON and fireOFF, with SPITFIRE being switched on or off, respectively. In both simulations, the dynamic vegetation module of ORCHIDEE was de-activated, and a current-day vegetation distribution map (converted into the 13-PFT map in ORCHIDEE based on IGBP 1-km vegetation map, http://webmap.ornl.gov/wcsdown/dataset.jsp?ds_id=930) was used as the static land cover. Here, fire-vegetation-climate feedback was not included because the relative fractions of different PFTs remain the same over the simulation period. It means not only that fires associated with land cover change (deforestation fires) are not included, but also that wildfires are not affected by changing PFTs.

Agricultural fires are not simulated in the model for two reasons. First, the timing of agricultural burning is strongly constrained by the sowing and harvest date (Magi et al., 2012). An enhanced crop phenology module is under development for ORCHIDEE and this will allow precise agricultural fire seasons to be included in the future. Second, agricultural fires are normally under strict human control and the spread and size of fires are limited by field size; they are thus very different from wildfires and warrant a special modelling approach. Carbon emissions from tropical and boreal peat fires are not explicitly simulated, although the model does simulate some burned fraction in tropical regions where deforestation fires dominate. Because the model could capture the "climate window" when the climate is relatively dry and deforestation fires are possible. Thus even though the model does not explicitly simulate deforestation fires using a land-cover-change approach, it does capture some fire activities in the region dominated by deforestation fires, and simulate them like natural wildfires. Figure S1 compares simulated and GFED3.1 emissions for the tropical region of 20°S–20°N for different types of fire averaged over 1997–2009. The simulated fire emissions were partitioned into forest and grassland fires, and the GFED3.1 emissions were partitioned into "deforestation + forest", "woodland + savanna", and "agriculture + peat". The model could capture part of forest and deforestation fire emissions in this region (simulated 0.28 Pg C yr^{-1} against GFED3.1 0.44 Pg C yr^{-1}, of which deforestation fires account for 0.33 Pg C yr^{-1} and naturally occurring forest fires 0.11 Pg C yr^{-1}), because simulated total forest fire emissions in this region are larger than those from natural forest fires as given by GFED3.1 data. The simulated emissions are slightly lower than GFED3.1 data, even when emissions from agriculture and peat fires are excluded (simulated 1.38 Pg C yr^{-1} for forest + grassland; against GFED3.1 1.50 Pg C yr^{-1} for deforestation + forest + woodland + savanna, and 1.63 Pg C yr^{-1} when agriculture and peat are further included). This shows that the model has limited capability in capturing fire emissions in tropical regions.

Both fireON and fireOFF simulations followed the same protocol, which comprised three steps. For both simulations, the model was first run for 200 years (including a 3000-year soil-only spin-up to speed up the equilibrium of slow and passive soil carbon pools) starting from bare ground without fire, with atmospheric CO_2 being fixed at the pre-industrial level (285 ppm) and climate data of 1901–1930 being cycled. For the fireON simulation, after this first spin-up, the model was run for a second spin-up of 150 years with the fire model being switched on, to allow carbon stocks to reach an equilibrium state under pre-industrial fire disturbance. For this second spin-up with fires, atmospheric CO_2 was set at pre-industrial level and climate data of 1901–1930 were cycled. We verify that during last 50 years of this second spin-up, the mineral soil carbon stock (i.e., the sum of active, slow and passive soil carbon pools in the model) varies within 0.1% and no significant trend exists for simulated global total carbon balance. This simulation was followed by a third transient simulation for 1850–2012, with variable climate, atmospheric CO_2 and population density data.

The fireOFF simulation follows the same first spin-up, second spin-up and transient steps as the fireON simulation, except that the fire model is switched off throughout all simulations. The climate data used for 1901–2012 are 6-hourly CRUNCEP data (http://dods.extra.cea.fr/store/p529viov/cruncep/V4_1901_2012/readme.htm). During the period 1850–1900 when CRUNCEP climate data were not available, the data of 1901–1910 were used and cycled. Lightning data were retrieved from the High Resolution Monthly Climatology of lightning flashes by the Lightning Imaging Sensor–Optical Transient Detector (LIS/OTD) (http://gcmd.nasa.gov/records/GCMD_lohrmc.html). The LIS/OTD dataset provides mean monthly flash rates over the period of 1995–2000 on a 0.5^{o} grid, which were cycled each year throughout the simulation. The annual historical population density data were retrieved from the Netherlands Environmental Assessment Agency (http://themasites.pbl.nl/tridion/en/themasites/hyde/download/index-2.html). Please refer to Yue et al. (2014) for the detailed information on these input datasets.

For the fireON simulation, after the second spin-up, there is a global carbon sink of 0.19 Pg C yr^{-1} over the last 50 years prior to the transient simulation due to the not-fully complete equilibrium of slow soil carbon pools. We verified that this sink has a negligible trend (annual trend of 0.003 Pg C yr^{-1}). For the fireOFF simulation, the residual sink before the transient simulation is 0.17 Pg C yr^{-1} (with a negligible annual trend of -0.001 Pg C yr^{-1}). Because the ORCHIDEE version used here is computationally expensive, we did not run the model until a complete carbon saturation state. The simulated annual global total net biome production (NBP) during 1901–2012 was bias-corrected for this incomplete spin-up by subtracting the remaining positive NBP over the last 50 years of the second spin-up. No spatial corrections were made.

2.4 Land-atmosphere carbon flux conventions

We define NEP, the net ecosystem production, as:

$$NEP = NPP - RH - CH \qquad (1)$$

where NPP is net primary production, RH is the heterotrophic respiration, and CH is the harvested crop yield. We assume that crop harvest is released into the atmosphere within the year when being harvested. Next, we define NBP, the net biome production as:

$$NBP = NEP - FE \qquad (2)$$

where FE is fire carbon emission. In case of fireOFF simulation, fire carbon emissions would be zero. If we do not include other components of the carbon balance term (e.g., herbivore consumption, biogenic volatile organic compound emissions, lateral carbon transfer by rivers and erosion), NBP is here considered as land carbon sink. We expect that fires reduce this carbon sink, and define the "fire-induced sink reduction" as:

$$SR_{fire} = NBP_{OFF} - NBP_{ON} \qquad (3)$$

where NBP_{OFF} is NBP by fireOFF simulation and NBP_{ON} is NBP by fireON simulation. We further define a term "sink efficiency (SE)"as NBP divided by NPP, which describes the fraction of NPP used to sequester carbon from the atmosphere.

2.5 Evaluation datasets and other datasets

The GFED3.1 fire carbon emissions from the CASA biosphere model forced by GFED3.1 burned area data were used to evaluate simulated fire carbon emissions (van der Werf et al., 2010). Much work has been done to calibrate the CASA model against observations, e.g., in terms of productivity and NPP allocation (van der Werf et al., 2006; 2010). Carbon emissions from six different fire types are identified in GFED3.1 data, namely forest fire, grassland fire, woodland fire, agricultural fire, deforestation and peatland fires. For the convenience of description, emission sources of the former three types of fire are tentatively referred to as natural sources (that ORCHIDEE-SPITFIRE simulates explicitly), and those of the latter three types as anthropogenic sources (that ORCHIDEE does not explicitly include, although it is able to capture part of the deforestation fire emissions as explainedin Sect. 2.3). Note that the grouping of different emission sources in GFED3.1 data does not necessarily reflect the exact nature of different fire types. For example, peat fires in tropics are mainly due to intentional drainage followed by burning to remove a (logged) forest (thus anthropogenic, e.g., Marlier et al., 2015), while in northern high-latitude regions peatland fires might be due to drought (thus natural, e.g. Turetsky et al., 2011).

Not all anthropogenic carbon emissions (mainly from fossil fuel consumption, cement production and deforestation) into the atmosphere remain there, and part of them are absorbed by the terrestrial ecosystem (land sink) and the ocean (ocean sink). The so-called residual carbon sink in land ecosystems can be obtained by subtracting the annual CO_2 accumulation in the atmosphere and the ocean sink from the total anthropogenic carbon emissions (Le Quéréet al., 2013). This residual sink was used here to be compared with simulated carbon sink.

The fire variability at global and regional scales is known to relate to the ENSO mode of climate variability (Kitzberger et al., 2001; Prentice et al., 2011; van der Werf et al., 2004), mainly affecting the tropics but with global teleconnections (Kiladis and Diaz, 1989). The Southern Oscillation Index (SOI, http://www.bom.gov.au/climate/current//soihtm1.shtml) is an indicator of the development and intensity of El Niño or La Niña events in the Pacific Ocean (negative values of the SOI below -8 often indicate El Niño episodes and the reverse La Niña episodes). SOI was used here to investigate the fire-induced sink reduction in relation to this large-scale climate oscillation.

Finally, the fire pyrome distribution map of Archibald et al. (2013) was used to relate the influence of fires on NBP to different fire pyromes (Fig. S2). Five fire pyromes were identified by using a Bayesian clustering algorithm with information on key characteristics of fire regimes – size, frequency, intensity, season and extent. The five pyromes are: FIL (Frequent–Intense–Large); FCS (Frequent–Cool–Small); RIL (Rare–Intense–Large) (RIL); RCS (Rare–Cool–Small) and ICS (Intermediate–Cool–Small). Frequent fires (FIL and FCS) are characterized by large annual burned fractions in areas with a relatively long fire season. Australia has large, intense fires (FIL pyrome), whereas in Africa, smaller less intense fires (FCS pyrome) dominate. Rare fires (RIL and RCS pyromes) are found in areas with a short fire season, dominating in temperate and boreal regions (see Table 1 and Fig. 2 in Archibald et al., 2013 and the descriptions for more information).

3 Results and discussion

3.1 Calibrated productivity and simulated burned area

The calibration of carboxylation rates significantly improved the model-observation agreement in terms of the distribution of GPP as a function of annual precipitation (Fig. 1). The calibrated model is also able to capture the productivity decrease when annual precipitation exceeds 3000 mm (Fig. 1). The simulated global GPP for 1982–2010 is 125 Pg C yr^{-1}, close to the 119 +/- 6 Pg C yr^{-1} given by Jung et al. (2011). The simulated global NPP for 2000–2009 is 61 Pg C yr^{-1}, close to the 54 Pg C yr^{-1} estimated by Zhao and Running (2010) using MODIS satellite data and light-use efficiency conversion factors.

The simulated global burned area for 2001–2006 is 239 Mha yr^{-1}, lower than the original 346Mha yr^{-1} before calibration (Yue et al., 2014). This reduction of simulated burned area mainly occurs in the regions with high fire frequency where GPP was decreased by the calibration (Fig.

2). After the GPP calibration, the burned fraction of grassland and savanna ecosystems in Africa, Australia and South America, became underestimated compared to GFED3.1 (Fig. 2b and d). The reduction in simulated burned fraction is related to the reduced amount of dead fuel on the surface (Fig. S3) in response to the lower GPP – the latter reduces fire spread rates and fire sizes.

3.2 Temporal and spatial patterns of global fire carbon emissions

3.2.1 Comparison of simulated carbon emissions with GFED3.1 at the global scale

The simulated mean annual global fire carbon emissions for 1997–2009 are 2.1 Pg C yr^{-1}, close to the estimate of 2.0 Pg C yr^{-1} by GFED3.1 data, where emissions from both natural and anthropogenic sources are included (Fig. 3), and higher than the 1.5 Pg C yr^{-1} when peat, deforestation and agricultural fires are excluded from GFED3.1. The model also simulates lower IAV of emissions than GFED3.1, giving a coefficient of variation of 0.05, compared to 0.18 for the GFED3.1 data (0.15 when only natural sources are included in GFED3.1).

The interannual variability of fire carbon emissions is known to be partially decoupled from that of burned area (van der Werf et al., 2006), mainly because emission variability is driven by forest fires having higher fuel consumption, whereas burned area variability is driven by savanna fires with relatively large burned fraction but low fuel consumption. At the global scale, the IAV of fire carbon emissions is simulated to be closely related to that of burned area (Fig. S4, giving a correlation coefficient of 0.88 over 1997–2009 – all data detrended). In contrast, the correlation coefficient between GFED3.1 natural source emissions and burned area is 0.52 over the same period (0.04 when emissions from both natural and anthropogenic sources are included), i.e., smaller than ORCHIDEE-SPITFIRE. Thus the IAV of carbon emissions is more strongly coupled with that of burned area in ORCHIDEE than in GFED3.1, because emissions are dominated by burning of litter (from grassland, savanna and forest) and are less driven by forest fires that involve large amount of live biomass burning.

3.2.2 Comparison of simulated carbon emissions with GFED3.1 for different regions

Annual fire carbon emissions simulated by ORCHIDEE-SPITFIRE are compared with GFED3.1 data for 1997–2009 for different regions in Fig. 4 (see figure caption for expansion of GFED region abbreviations and Fig. S5 for region distribution). The three regions with the most frequent fires, Northern Hemisphere Africa (NHAF), Southern Hemisphere Africa (SHAF) and Australia (AUST) have total fire emissions of 1.17 Pg C yr^{-1} and contribute 59% of the global total emissions in GFED3.1. In ORCHIDEE, annual emissions are 1.18 Pg C yr^{-1} for these three regions; an overestimation in NHAF being partly compensated by underestimation in SHAF.

The GFED3.1 data have very low emissions in Temperate North America (TENA), Middle East (MIDE), Central Asia (CEAS) and Europe (EURO) (50 Tg C yr^{-1} in total for the three regions; 2.5% of the global total), whereas ORCHIDEE-SPITFIRE simulates much higher emissions (294 Tg C yr^{-1}; 14% of the global total) possibly because forest fire control measures (Fernandes et al., 2013; Keeley et al., 1999) and forest management in temperate countries (Fang et al., 2001; Luyssaert et al., 2010) are not modelled; this leads to higher burned area and/or higher fuel load in the model. The overestimation of emissions in these three regions is partly driven by the overestimation of burned area (annual burned area of 70.2 Mha yr^{-1} in the model versus 10.1 Mha yr^{-1} in GFED3.1 in Table 1).

The three regions where the model underestimates carbon emissions are Boreal Asia (BOAS), Southeast Asia (SEAS) and Equatorial Asia (EQAS), with simulated emissions of 103 Tg C yr^{-1} (4.9% of the global total), compared with 412 Tg C yr^{-1} in GFED3.1 (21% of the global total). The low bias of emissions in BOAS and SEAS is explained by the underestimation of burned area (Table 1) whereas for EQAS, underestimates in both burned area and fuel consumption by the model are found (Table 1) (in particular, peat burning that dominates emissions in 1997–98 in SEAS is lacking in the model, see van der Werf et al., 2008). This points to the need to explicitly include deforestation and peat fires, which are associated with a high amount of fuel consumption (van der Werf et al., 2010).

3.2.3 Fire fuel consumption and latitudinal pattern of emissions

Simulated fuel consumption (g C per m^2 of area burned) in fire is compared to GFED3.1 data in Fig. 5. Both ORCHIDEE-SPITFIRE and GFED3.1 show a large amount of fuel consumption in boreal regions. But fuel consumption in the Russian boreal forest is smaller in the model than GFED3.1 (simulated 400–2000 g C m^{-2} compared to 2000–5000 g C m^{-2} in GFED3.1). The model also fails to capture the high fire fuel consumption (5–20 kg C m^{-2}) at the southern edge of the Amazonian rainforest and in Southeast Asia, which are associated with deforestation fires or peat fires (see also Fig. 6 and Fig. 13 in van der Werf et al., 2010). The fire fuel consumptions for savannas and woodland savannas in Africa and Australia are higher in the model than GFED3.1, with fuel consumption in northern Africa of 1000–2000 g C m^{-2} against 200–1000 g C m^{-2} by GFED3.1. In southern Africa, ORCHIDEE produces fuel consumption of 1000–2000 g C m^{-2} against only 400–1000 g C m^{-2} in GFED3.1. The simulated higher fuel consumption in tropical savannas and woodland savannas might be due to a combination of overestimated fuel load and combustion completeness, which is discussed in more detail in section 3.2.4. Further, we acknowledge the fact that ORCHIDEE can have grass and tree PFTs coexisting on the same grid point, but does not describe woody savannas or miombo forests where grass and trees compete locally for water, light and nutrients and could have lower fuel consumptions due to the presence of fire-resistant tree species (Hoffmann et al., 2012).

Figure 6 shows carbon emissions per grid cell area (g C per m^2 of grid cell) calculated as the product of fire fuel consumption (Fig. 5) and burned fraction (Fig. 2). Because underestimated burned fractions in African and Australian savannas and woodland savannas compensate for overestimated fuel consumption, fire carbon emissions per grid cell for these regions are of similar magnitude to those in GFED3.1. Emissions per grid cell area in southern African woodland savanna are even underestimated by ORCHIDEE (10–50 g C m^{-2} yr^{-1}) compared with GFED3.1 (50–200 g C m^{-2} yr^{-1}), due to the great underestimation in burned area.

By looking at the latitudinal distribution of burned area and emission, the systematic error in ORCHIDEE's estimated emissions can be clearly related to that in burned area (Fig. 7). The underestimation of burned area in tropical and subtropical regions (30°S–15°N) (Fig. 2) is compensated by the overestimated fire fuel consumption. In southern tropical regions (30°S–0°), carbon emissions are still underestimated (by 270 Tg C yr^{-1}) despite this compensation effect, whereas in northern tropical regions (0°–15°N), the compensation leads to overestimated emissions (by 190 Tg C yr^{-1}) compared with GFED3.1.

3.2.4 Attributing systematic emission errors to burned area and fuel consumption at regional level

Table 1 compares mean annual simulated and GFED3.1 emissions for 1997–2009 for different regions. The model bias of emissions is qualitatively attributed to those of burned area and fuel consumption. Table S2 further compares NPP and fire combustion completeness between the model and the GFED3.1 data (where NPP is from the CASA biosphere model, with all GFED3.1 data in Table S2 obtained from Table 4 in van der Werf et al., 2010). For all regions (except NHAF and AUST) where emissions are overestimated by the model (TENA, CEAM, NHSA, SHSA, EURO, MIDE, CEAS), there is a coincident overestimation in burned area, which sometimes overrides the underestimated fuel consumption in regions such as CEAM. Regions where emissions are underestimated also show underestimated burned area (with the exception of BOAS), some of them also having underestimated fuel consumption (EQAS).

The simulated NPP regional averages are in general agreement with those from the CASA model reported by van der Werf et al. (2010) (Table S2), indicating that the simulated fuel load might be comparable to GFED3.1 data, and that systematic errors in fuel consumption might be dominated by errors in the combustion completeness of different fuels. On the one hand, simulated combustion completeness for litter agrees well with the values used in GFED3.1; but on the other hand, combustion completeness for the litter and aboveground live biomass combined is much higher in ORCHIDEE than GFED3.1 over BOAS, BONA, MIDE, NHAF, SHAF and AUST, and much lower over EQAS. This might reflect a higher or lower simulated combustion completeness of tree live biomass, which needs further investigation. The higher simulated combustion completeness for litter and live biomass combined in NHAF, SHAF and AUST contributes to the higher fuel consumptions in these regions, given the fact that simulated NPP is rather similar to GFED3.1 over these regions (except for NHAF where the simulated NPP is 40% higher than GFED3.1 and combustion completeness is 2.6 times higher). A recent comparison among different fuel load products by Pettinari et al. (2015, to be submitted) also indicates that our simulated fuel loads in savannas and shrublands are higher than their fuel-model-based data, consistent with the higher NPP in Africa and Australia (Table S2). At the same time, one should also keep in mind that GFED3.1 is not a completely observation dataset, but is another model calculation of fire emissions. Given the availability of the comprehensive fuel combustion field data recently compiled by van Leeuwen et al. (2014), more careful calibration and validation of the simulated combustion completeness for different fuel types could be performed in the future.

Finally, the combustion completeness (CC) values used for the 100 and 1000h dead fuel for temperate forests, boreal forests and grasslands are slightly different from those reported by van Leeuwen et al. (2014). The mean CC values for the latter three biomes as updated in van Leeuwen et al. (2014) are 0.69+/-0.13, 0.47+/-0.16, and 0.81+/-0.16 respectively. The CC values for boreal forests and grasslands used here are within the uncertainty range by van Leeuwen et al. (2014). The CC value for temperate forests is higher than van Leeuwen et al. (2014). We developed a simple approach to adjust the simulated fire carbon emissions for these three biomes by multiplying the simulated emissions by the ratio of our CC values to those of van Leeuwen et al. (2014), and found that the global total fire carbon emissions remain almost the same (2.1 Pg C yr^{-1} versus 2.08 Pg C yr^{-1} before and after adjustment for 1997–2009). This is because the smaller CC values used for temperate and boreal forests are compensated for by the larger CC value of grasslands used in the model.

3.3 The role of fires in the terrestrial carbon balance

3.3.1 The simulated carbon balance for the last decade (1993–2012)

Figure 8 shows the percentage of NPP emitted by fire over the last decade (2003–2012). Regions with frequent burning show a higher fraction of NPP being returned to the atmosphere by fire. Yet, heterotrophic respiration remains the dominant pathway for returning NPP to the atmosphere, accounting for 85.7% of the global NPP (91.1% when agricultural harvest is included, the CH term in Eq. 1). Fire carbon emissions account for 3.4% of NPP, with the remaining 5.2% of NPP being accumulated in the biosphere as a carbon sink (NBP) (As mentioned in section 2.3, the remaining positive NBP of 0.19 Pg C yr^{-1} is subtracted here, taking account for 0.3% of NPP). The simulated global NPP for 2003–2012 is 60 Pg C yr^{-1} in the fireON simulation, with 2.1 Pg C yr^{-1} emitted as fire emissions, and 3.1 Pg C yr^{-1} stored as NBP. The simulated NBP is within the 1-sigma error of the observed residual sink for the same period, which is of 2.8+/- 0.8 Pg C yr^{-1} (see Le Quéréet al., 2013 for uncertainty estimation). Fire carbon emissions as a percentage of NPP for 1901–2012 average show little difference with 2003–2012 average in terms of spatial distribution, except that the percentages are slightly lower than 2003–2012 average for grassland fires such as in central and eastern Asia (Fig. S6).

3.3.2 Fire-induced terrestrial carbon sink reduction for 1901–2012

The different components of global carbon fluxes for the fireON and fireOFF simulations are shown in Fig. 9. Net primary production (NPP) for fireON and fireOFF are very similar (NPP is 6 Tg C yr^{-1} higher in fireOFF for 1901–2012) (Fig. 9a). This greater NPP in the fireOFF simulation compared with fireON might be underestimated, because land-cover change or vegetation dynamics were ignored in the simulations (For example, bigger forest coverage would have occurred in the fireOFF simulation if vegetation dynamics were modelled).

The carbon sink in fireOFF is greater than that in fireON (Fig. 9c). This is because fire emissions (1.91 Pg C yr^{-1} for 1901–2012) are greater than the heterotrophic respiration excess in fireOFF (Fig. 9b, by 1.62 Pg C yr^{-1} averaged over 1901–2012). The fire-induced sink reduction (SR_{fire}) amounts to 0.32 +/- 0.09 Pg C yr^{-1} over 1901–2012, or 20% of the fireOFF NBP. This sink reduction would have been bigger if deforestation (land-cover change) and peat fires were included in the model because carbon released from these fires is more likely an irreversible net carbon source, i.e., it will not be re-absorbed by post-fire plant recovery on a centennial time scale.

The small fire-induced carbon sink reduction obtained in this study, when only natural wildfires are modelled and with static vegetation cover, implies that if carbon stocks in the fuel (dominated by litter or organic soil except in cases of peat and deforestation fires) were not consumed in fires, they would have been decomposed and have contributed to the heterotrophic respiration. This suggests a "fire respiration partial compensation" in the model. I.e., fire carbon emissions are somewhat analogous to heterotrophic respiration, and when fires are extreme their emissions would exceed far their role of respiration compensation, causing a larger net reduction in carbon sink compared to a world without fire. The sink reduction variability is closely correlated with fire emission anomalies during 1901–2012 (with a correlation coefficient of 0.71, Fig. 9d). Fire carbon emissions show an acceleration of 1.8 Tg C yr^{-2} prior to 1970, and a trend of 6 Tg C yr^{-2} after 1970, with both trends being significant at the 0.05 level.

Our simulated cumulative land carbon sink (NBP) for 1959–2012 is 109.6 Pg C (with 80.8 Pg C stored in live biomass and 28.8 Pg C in litter and soil), which is close to the cumulative residual sink of 105.9 Pg C (Le Quéréet al., 2013). The cumulative land sink in fireOFF is 127.2 Pg C, suggesting a cumulative sink reduction of 17.6 Pg C by fire since 1959. The correlation coefficient between detrended time series of NBP by the fireON simulation and the residual sink is 0.59, indicating that the model is moderately successful at capturing the IAV of the carbon sink by the terrestrial ecosystem.

Prentice et al. (2011) pointed out that fire emissions account for one-third and one-fifth of the IAV of the 1997–2005 global carbon balance as indicated by atmospheric inversions, when emissions were from the GFED3.1 data and simulated by the vegetation model LPX, respectively. In our study, fire carbon emissions explained 20% of the IAV of simulated NBP (which is the R^2 of the linear regression of detrended annual NBP against simulated carbon emission), congruent with their results.

3.3.3 Fire-induced carbon sink reduction for extreme high and low fire years

We selected ten "high fire years" years as the ten years with highest global fire-induced sink reduction (SR_{fire}) during 1901–2012 (Fig. 9d), and ten "low fire years" as the years with the ten lowest global SR_{fire} during the same period. The average SR_{fire} for the high fire years is 0.49 Pg C yr^{-1} (23% of the fireOFF NBP), compared with an average SR_{fire} of 0.17 Pg C yr^{-1} (7% of the fireOFF NBP) for the ten low fire years.

The Pearson correlation coefficient (r) between the SR_{fire} time series and other model variable or climatic drivers (temperature, precipitation) was used to investigate the driving factors for fire-induced sink reduction. The SR_{fire} variation was found to be best explained by fire numbers ($r = 0.65$, $p < 0.05$) within the model, since fire numbers are also driving the variation of burned area ($r = 0.81$, $p < 0.05$). SR_{fire} is also positively correlated with land surface temperature ($r = 0.16$, $p = 0.08$), and negatively correlated with precipitation ($r = -0.23$, $p < 0.05$), although the correlation is fairly weak.

The opposite of SR_{fire} is positively correlated with the Southern Oscillation Index (SOI) ($r = 0.29$, $p < 0.05$, Fig. 10), suggesting that global fire-induced sink reduction is significantly related to the change in the tropical Pacific sea-surface temperature gradient, because of its strong influence over global rainfall (Ropelewski and Halpert, 1987, 1996). The El Niño state (i.e., low SOI value) of climate oscillation generally coincides with larger sink reduction by fires (i.e., larger SR_{fire}), and La Niña with smaller reduction. Indeed, seven out of the ten high fire years occur during El Niño episodes, and six out of the ten low fire years occur during La Niña episodes (The diagnosis of El Niño and La Niña episodes is given by the Bureau of Meteorology of Australian government, http://www.bom.gov.au/climate/enso/lnlist/). SR_{fire} is more strongly related with SOI in tropical regions than at the global scale thanks to the more direct impacts of ENSO events (for 30^{o}S–30^{o}N, the relationship between $-SR_{fire}$ and SOI yields $r = 0.33$ with $p < 0.05$). This region contributes 82 and 72% of global total emissions and carbon sink, respectively.

As we did not include agricultural fires, deforestation fires and peat fires in our simulation, the analysis of fire-induced sink reduction related to climate variations presented here mainly represents a scenario of naturally occurring fires. Globally, the 1997-1998 fire emissions anomaly is underestimated in the model, principally related to the fact that the anthropogenic peatland and deforestation burning in tropical Asia and America (Field et al., 2009; Page et al., 2002; van der Werf et al., 2004, 2010) are not included. The underestimated IAV in fire carbon emissions by the model might lead to underestimated temporal variability in SR_{fire}, thus the actual correlation between fire-induced sink reduction and SOI over the historical period might be underestimated.

Despite the fact that systematic bias exists for simulated burned area, as global total fire carbon emissions are constrained with GFED3.1 estimate, the estimated long-term average SR_{fire} remains reliable. To verify this, we forced the model with observed GFED3.1 burned area data for

1997-2009 on a monthly time step and used the regional specific combustion completeness values as reported in van der Werf et al., 2010 (Table 4 in van der Werf et al., 2010 for the 14 regions). The forced simulation yields annual global fire carbon emissions of 1.8 Pg C yr^{-1} for 1997-2009 and an SR_{fire} of 0.39 Pg C yr^{-1}, close to the fire emissions of 2.1 Pg C yr^{-1} and SR_{fire} of 0.36 Pg C yr^{-1} as given by the prognostic simulation.

The suggested "respiration partial compensation" by fires (i.e., larger sink reduction with more extreme fires), and the strong relevance of SR_{fire} to climatic variations (i.e., larger sink reduction during warm and dry El Niño years) have implications for the future role of fires in the terrestrial carbon balance. Studies show that climate warming in recent decades has already driven boreal fire frequency to exceed its historical limit (Kelly et al., 2013) and resulted in increased carbon loss (Hayes et al., 2011; Mack et al., 2011; Turetsky et al., 2011). The ENSO-driven climate variability, with its strong influence on global precipitation, has widespread impact on fire activity across the globe (Carmona-Moreno et al., 2005; Kitzberger et al., 2001; Chen et al., 2011; Prentice et al., 2011). With continuing anthropogenic disturbances on the climate system by greenhouse gas emissions, the evidence from multiple-modelling exercises indicates a likely increase in the frequency of extreme El Niño events and droughts in the 21st century (Cai et al., 2014; Meehl and Washington, 1996; Prudhomme et al., 2013; Timmermann et al., 1999). These projections in turn lead to projected increases in fire activities and emissions (Flannigan et al., 2009; Kloster et al., 2012). As a further consequence, the capacity for land ecosystems to sequester carbon is likely to be further diminished in the future.

3.3.4 Simulated fire-induced sink reduction and comparison with Li et al.

Li et al. (2014) investigated the role of fires in the terrestrial carbon cycle using the CLM4.5 model and a similar modelling approach (fire-on versus fire-off simulations, with prescribed historical land cover and a de-activated dynamic vegetation module). They found that fires reduced the terrestrial carbon sink by on average 1.0 Pg C yr^{-1} during the 20th century. Our simulated sink reduction (0.32 Pg C yr^{-1} for 1901–2012) is smaller than theirs. However, fire carbon emissions (called the *fire direct effect* by Li et al., 2014) from the two studies are similar (1.9 Pg C yr^{-1} by both studies for the 20th century). Therefore, the difference in fire sink reduction between the twostudies must be due to differences in other flux estimates (NPP and heterotrophic respiration).

Li et al. (2014) estimated that fire reduced global NPP by 1.9 Pg C yr^{-1}, but the heterotrophic respiration was reduced by an even larger amount (2.7 Pg C yr^{-1}), resulting in a higher NEP of 0.9 Pg C yr^{-1} in their fire-off simulation (called *fire indirect effect*). We alsofind a higher heterotrophic respiration in our fireOFF simulation (by on average 1.62 Pg C yr^{-1} over 1901–2012) but the simulated NPP difference is negligible (6 Tg C yr^{-1} higher in fireOFF than fireON). The NPP reduction by fire is probably underestimated in our study, because land-cover change fires are not accounted for, and grassland or agricultural land converted from forest has much lower NPP than it had prior to conversion (Houghton et al., 1999). Thus the NEP increase by switching fire off might also be underestimated, which leads to underestimated sink reduction by fire.

Lastly, our study shares two prominent uncertainties in quantifying the role of fires in the terrestrial carbon cycle with those discussed by Li et al. (2014). Firstly, the vegetation dynamics module was switched off in our simulation, and this might limit the terrestrial carbon sink by land ecosystems in a world without fire. Previous studies have pointed out that if all fires were suppressed tree cover would expand in regions where current grassland or woodland ecosystems are maintained by fires (Bond et al., 2005; Staver et al., 2011); and that the expanded forest coverage would increase land carbon stock (Bond et al., 2005). Secondly, because ORCHIDEE was not coupled to an atmosphere model, the atmospheric concentration changes for various gases released by fire, or a complete fire-vegetation-climate feedback, as discussed in the Introduction, were not included.

3.3.5 The role of fires in the terrestrial carbon balance in relation to fire pyromes

We compared fire fuel consumption, the fraction of NPP returned via fire emissions and its temporal variation, and carbon sink efficiencies (SE) for fireOFF and fireON simulations for the five pyromes defined by Archibald et al. (2013) (see Sect. 2.5). The temporal variation for the fraction of NPP lost to fire emissions is examined as the coefficient of variation during 1901–2012, which is the standard deviation divided by the mean.

According to model simulation, Frequent–Intense–Large (FIL) and Frequent–Cool–Small (FCS) fires have higher fuel consumption than infrequent Rare–Intense–Large (RIL) and Rare–Cool–Small (RCS) fires (Fig. 11), fuel consumption being the highest in the FCS pyrome (1.2 kg C m^{-2}) and the lowest in the RCS pyrome (0.6 kg C m^{-2}). Correspondingly, the ratio of fire emissions to NPP is also higher in frequent-fire pyromes than in infrequent ones, but the temporal variation of this fraction is higher for RCS and RIL pyromes. Regions with infrequent fires (RCS, RIL and ICS) have greater sink efficiency than those with frequent ones (FIL, FCS) for the fireOFF simulation. This pattern remains for the fireON simulation, which gives smaller sink efficiency than fireOFF for all the pyromes, due to the adverse effects of fires on the land carbon sink. Consequently, the sink efficiency as reduced by fires remains higher in infrequent-fire pyromes (being the highest in the RIL pyrome) than frequent ones (being the lowest in the FIL pyrome).

It is reasonable to find that frequent fires have higher fuel consumption than small cool ICS and RCS fires, because the latter are generally human-controlled burning with limited fuel load (Archibald et al., 2013). However, intuitively, the Rare–Intense–Large (RIL) fires are expected to have at least comparable, if not larger, fuel consumption than the FIL and FCS pyromes, since their spatial extent covers the North American boreal forest biome where large amounts of soil (and biomass) carbon stocks are exposed to burning. Our model simulation does show a high amount of fire fuel consumption in North American boreal forests: 1–5 kg C m^{-2} (Fig. 5), comparable to that reported in regional studies (French et al., 2011; Kasischke and Hoy, 2012). A closer examination of the fire pryome distribution map (Fig. S2) reveals that some of the grassland fires in central and eastern Asia and inland Australia are also classified as RIL fires, which have a rather low simulated fuel consumption rate (1–200 g C m^{-2}, Fig. 5). Thus the simulated fuel consumption for RIL fires is a mean value for all above regions (including boreal forests in Eurasia as well), which is lower than frequent fires.

We also find the carbon sink efficiencies for infrequent-fire pyromes are higher than frequent ones for both fireON and fireOFF simulations, probably because more forests are located in infrequent-fire pyromes (Table 1 in Archibald et al., 2013). The sink efficiency reduction (SE_{OFF}-SE_{ON}) by fires is the highest in the RIL pyrome, congruent with a higher Emission-to-NPP fraction. If we examine the percentage of fire-induced sink efficiency reduction to SE_{OFF}, the FIL, FCS and RIL pyromes emerge again to have higher percentage than RCS and ICS pyromes (data not shown). This indicates that frequent fires and infrequent-large fires reduce the carbon sequestration capacity of land ecosystems to a higher extent. Note that as an initial attempt to understand the role of fires in carbon cycling for different pyromes (such as that for different biomes), great uncertainties exist in the modelling results presented here. Sources of uncertainties include that agricultural and deforestation fires were included in Archibald et al. (2013) but not in our model; errors and uncertainties exist in simulated fire fuel consumption and fire emissions; the combustion difference between surface fires in boreal Eurasian forests and crown fires in North American boreal forests (de Groot et al., 2013; Wirth, 2005) is lacking in the model; uncertainties exist in the classification of fire pyromes.

4 Summary and conclusions

In this study, we used the ORCHIDEE land surface model with recently integrated SPITFIRE model to estimate the role of fires in the terrestrial carbon balance for the 20th century. The simulated global fire carbon emissions for 1997–2009 are 2.1 Pg C yr^{-1}, close to the 2.0 Pg C yr^{-1} as estimated by the GFED3.1 data (when all types of fires are included), owing to error compensation among different regions in the model. Fire carbon emissions are mainly underestimated in southern hemisphere tropical regions and this error is compensated by an overestimation in temperate ecosystems. The regional emission errors are found to be coincident with the errors in simulated burned area, with the exception that fire fuel consumption is underestimated in regions featuring peatland or deforestation fires such as equatorial Asia, because these fires are not explicitly included in the model.

Fires reduced the terrestrial carbon uptake by an average of 0.32 Pg C yr^{-1} over the period 1901–2012, equivalent to 20% of the carbon sink in a world without fire. Our simulations suggest that fires have a "respiration partial compensation" (although the inclusion of dynamic vegetation in the model might change this). Fire emissions in low fire years mainly compensate for heterotrophic respiration that would occur without fire combustion, but emissions in extreme high fire years exceed far their "respiration partial compensation" and create larger reduction in the terrestrial carbon sink. This fire-induced sink reduction has been found to be significantly correlated with climatic variations including El Niño Southern Oscillation (ENSO), with larger sink reductions occurring in warm, dry conditions. This finding has an important implication for the future role of fires in the terrestrial carbon balance, because the capacity of terrestrial ecosystems to sequester carbon will be more likely diminished in a future climate with more frequent and intense droughts and more extreme El Niñoevents. This also implies that fires might significantly impact the climate-carbon response (known as the γ factor) as simulated by coupled climate-carbon models.

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References

Archibald, S., Lehmann, C. E. R., GómezsDans, J. L. and Bradstock, R. A.: Defining pyromes and global syndromes of fire regimes, Proc. Natl. Acad. Sci. U.S.A.,110(16), 6442–6447, doi:10.1073/pnas.1211466110, 2013.

Balshi, M. S., McGuire, A. D., Duffy, P., Flannigan, M., Kicklighter, D. W. and Melillo, J.: Vulnerability of carbon storage in North American boreal forests to wildfires during the 21st century, Global Change Biol., 15, 1491–1510, 2009.

Beck, P. S. A., Goetz, S. J., Mack, M. C., Alexander, H. D., Jin, Y., Randerson, J. T. and Loranty, M. M.: The impacts and implications of an intensifying fire regime on Alaskan boreal forest composition and albedo, Global Change Biol., 17(9), 2853–2866, doi:10.1111/j.1365-2486.2011.02412.x, 2011.

Bond, W. J., Woodward, F. I. and Midgley, G. F.: The global distribution of ecosystems in a world without fire, New Phytol., 165(2), 525–537, doi:10.1111/j.1469-8137.2004.01252.x, 2005.

Bowman, D. M. J. S., Balch, J. K., Artaxo, P., Bond, W. J., Carlson, J. M., Cochrane, M. A., D'Antonio, C. M., DeFries, R. S., Doyle, J. C., Harrison, S. P., Johnston, F. H., Keeley, J. E., Krawchuk, M. A., Kull, C. A., Marston, J. B., Moritz, M. A., Prentice, I. C., Roos, C. I., Scott, A. C., Swetnam, T. W., van der Werf, G. R. and Pyne, S. J.: Fire in the Earth System, Science, 324(5926), 481 –484, doi:10.1126/science.1163886, 2009.

Cai, W., Borlace, S., Lengaigne, M., van Rensch, P., Collins, M., Vecchi, G., Timmermann, A., Santoso, A., McPhaden, M. J., Wu, L., England, M. H., Wang, G., Guilyardi, E. and Jin, F.-F.: Increasing frequency of extreme El Nino events due to greenhouse warming, Nature Clim. Change, 4(2), 111–116, doi:10.1038/nclimate2100, 2014.

Carmona-Moreno, C., Belward, A., Malingreau, J.-P., Hartley, A., Garcia-Alegre, M., Antonovskiy, M., Buchshtaber, V. and Pivovarov, V.: Characterizing interannual variations in global fire calendar using data from Earth observing satellites, Global Change Biol., 11(9), 1537–1555, doi:10.1111/j.1365-2486.2005.01003.x, 2005.

Chen, Y., Randerson, J. T., Morton, D. C., DeFries, R. S., Collatz, G. J., Kasibhatla, P. S., Giglio, L., Jin, Y. and Marlier, M. E.: Forecasting Fire Season Severity in South America Using Sea Surface Temperature Anomalies, Science, 334(6057), 787–791, doi:10.1126/science.1209472, 2011.

Chuvieco, E., Giglio, L. and Justice, C.: Global characterization of fire activity: toward defining fire regimes from Earth observation data, Global Change Biol., 14, 1488–1502, 2008.

Dufresne, J.-L., Foujols, M.-A., Denvil, S., Caubel, A., Marti, O., Aumont, O., Balkanski, Y., Bekki, S., Bellenger, H., Benshila, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., Noblet, N. de, Duvel, J.-P., Ethé, C., Fairhead, L., Fichefet, T., Flavoni, S., Friedlingstein, P., Grandpeix, J.-Y., Guez, L., Guilyardi, E., Hauglustaine, D., Hourdin, F., Idelkadi, A., Ghattas, J., Joussaume, S., Kageyama, M., Krinner, G., Labetoulle, S., Lahellec, A., Lefebvre, M.-P., Lefevre, F., Levy, C., Li, Z. X., Lloyd, J., Lott, F., Madec, G., Mancip, M., Marchand, M., Masson, S., Meurdesoif, Y., Mignot, J., Musat, I., Parouty, S., Polcher, J., Rio, C., Schulz, M., Swingedouw, D., Szopa, S., Talandier, C., Terray, P., Viovy, N. and Vuichard, N.: Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5, Clim.Dyn., 40(9-10), 2123–2165, doi:10.1007/s00382-012-1636-1, 2013.

Fang, J., Chen, A., Peng, C., Zhao, S. and Ci, L.: Changes in Forest Biomass Carbon Storage in China Between 1949 and 1998, Science, 292(5525), 2320–2322, doi:10.1126/science.1058629, 2001.

Fernandes, P. M., Davies, G. M., Ascoli, D., Fernández, C., Moreira, F., Rigolot, E., Stoof, C. R., Vega, J. A. and Molina, D.: Prescribed burning in southern Europe: developing fire management in a dynamic landscape, Frontiers in Ecology and the Environment, 11(s1), e4–e14, doi:10.1890/120298, 2013.

Flannigan, M. D., Krawchuk, M. A., de Groot, W. J., Wotton, B. M. and Gowman, L. M.: Implications of changing climate for global wildland fire, Int. J. Wildland Fire, 18(5), 483–507, 2009.

French, N. H. F., de Groot, W. J., Jenkins, L. K., Rogers, B. M., Alvarado, E., Amiro, B., de Jong, B., Goetz, S., Hoy, E., Hyer, E., Keane, R., Law, B. E., McKenzie, D., McNulty, S. G., Ottmar, R., Pérez-Salicrup, D. R., Randerson, J., Robertson, K. M. and Turetsky, M.: Model comparisons for estimating carbon emissions from North American wildland fire, J. Geohys. Res., B, 116(G4), G00K05, doi:10.1029/2010JG001469, 2011.

Giglio, L., Randerson, J. T., van der Werf, G. R., Kasibhatla, P. S., Collatz, G. J., Morton, D. C. and DeFries, R. S.: Assessing variability and long-term trends in burned area by merging multiple satellite fire products, Biogeosciences, 7(3), 1171–1186, doi:10.5194/bg-7-1171-2010, 2010.

Gill, A. M. and Allan, G.: Large fires, fire effects and the fire-regime concept, Int. J. Wildland Fire, 17(6), 688–695, 2008.

De Groot, W. J., Cantin, A. S., Flannigan, M. D., Soja, A. J., Gowman, L. M. and Newbery, A.: A comparison of Canadian and Russian boreal forest fire regimes, Forest Ecology and Management, 294, 23–34, doi:10.1016/j.foreco.2012.07.033, 2013.

Field, R. D., Werf, G. R. van der and Shen, S. S. P.: Human amplification of drought-induced biomass burning in Indonesia since 1960, Nat. Geosci., 2(3), 185–188, doi:10.1038/ngeo443, 2009.

Hayes, D. J., McGuire, A. D., Kicklighter, D. W., Gurney, K. R., Burnside, T. J. and Melillo, J. M.: Is the northern high-latitude land-based CO2 sink weakening?, Global Biogeochem. Cycles, 25(3), GB3018, doi:10.1029/2010GB003813, 2011.

Hoffmann, W. A., Geiger, E. L., Gotsch, S. G., Rossatto, D. R., Silva, L. C., Lau, O. L., Haridasan, M. and Franco, A. C.: Ecological thresholds at the savanna-forest boundary: how plant traits, resources and fire govern the distribution of tropical biomes, Ecol. Lett., 15(7), 759–768, 2012.

Houghton, R. A., Hackler, J. L. and Lawrence, K. T.: The U.S. Carbon Budget: Contributions from Land-Use Change, Science, 285(5427), 574–578, doi:10.1126/science.285.5427.574, 1999.

Jin, Y., Randerson, J. T., Goetz, S. J., Beck, P. S. A., Loranty, M. M. and Goulden, M. L.: The influence of burn severity on postfire vegetation recovery and albedo change during early succession in North American boreal forests, J. Geohys. Res., B, 117(G1), G01036, doi:10.1029/2011JG001886, 2012.

Jung, M., Reichstein, M., Margolis, H. A., Cescatti, A., Richardson, A. D., Arain, M. A., Arneth, A., Bernhofer, C., Bonal, D., Chen, J., Gianelle, D., Gobron, N., Kiely, G., Kutsch, W., Lasslop, G., Law, B. E., Lindroth, A., Merbold, L., Montagnani, L., Moors, E. J., Papale, D., Sottocornola, M., Vaccari, F. and Williams, C.: Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations, J. Geohys. Res., B, 116(G3), G00J07, doi:10.1029/2010JG001566, 2011.

Kasischke, E. S. and Hoy, E. E.: Controls on carbon consumption during Alaskan wildland fires, Global Change Biol., 18(2), 685–699, doi:10.1111/j.1365-2486.2011.02573.x, 2012.

Keeley, J. E., Fotheringham, C. J. and Morais, M.: Reexamining Fire Suppression Impacts on Brushland Fire Regimes, Science, 284(5421), 1829–1832, doi:10.1126/science.284.5421.1829, 1999.

Kelly, R., Chipman, M. L., Higuera, P. E., Stefanova, I., Brubaker, L. B. and Hu, F. S.: Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years, Proc. Natl. Acad. Sci. U.S.A., 110(32), 13055–13060, doi:10.1073/pnas.1305069110, 2013.

Kiladis, G. N. and Diaz, H. F.: Global Climatic Anomalies Associated with Extremes in the Southern Oscillation, Journal of Climate, 2(9), 1069–1090, doi:10.1175/1520-0442(1989)002<1069:GCAAWE>2.0.CO;2, 1989.

Kitzberger, T., Swetnam, T. W. and Veblen, T. T.: Inter-hemispheric synchrony of forest fires and the El Niño-Southern Oscillation, Global Ecology and Biogeography, 10(3), 315–326, doi:10.1046/j.1466-822X.2001.00234.x, 2001.

Kloster, S., Mahowald, N. M., Randerson, J. T. and Lawrence, P. J.: The impacts of climate, land use, and demography on fires during the 21st century simulated by CLM-CN, Biogeosciences, 9, 509–525, doi:10.5194/bg-9-509-2012, 2012.

Kloster, S., Mahowald, N. M., Randerson, J. T., Thornton, P. E., Hoffman, F. M., Levis, S., Lawrence, P. J., Feddema, J. J., Oleson, K. W. and Lawrence, D. M.: Fire dynamics during the 20th century simulated by the Community Land Model, Biogeosciences, 7(6), 1877–1902, 2010.

Krinner, G., Viovy, N., de Noblet-Ducoudré, N., Ogée, J., Polcher, J., Friedlingstein, P., Ciais, P., Sitch, S. and Prentice, I. C.: A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, Global Biogeochem. Cycles, 19(1), GB1015, doi:10.1029/2003GB002199, 2005.

Langenfelds, R. L., Francey, R. J., Pak, B. C., Steele, L. P., Lloyd, J., Trudinger, C. M. and Allison, C. E.: Interannual growth rate variations of atmospheric CO2 and its δ13C, H2, CH4, and CO between 1992 and 1999 linked to biomass burning, Global Biogeochem. Cycles, 16(3), 21–1–21–22, doi:10.1029/2001GB001466, 2002.

Van Leeuwen, T. T., van der Werf, G. R., Hoffmann, A. A., Detmers, R. G., Rücker, G., French, N. H. F., Archibald, S., Carvalho Jr., J. A., Cook, G. D., de Groot, W. J., Hély, C., Kasischke, E.

S., Kloster, S., McCarty, J. L., Pettinari, M. L., Savadogo, P., Alvarado, E. C., Boschetti, L., Manuri, S., Meyer, C. P., Siegert, F., Trollope, L. A. and Trollope, W. S. W.: Biomass burning fuel consumption rates: a field measurement database, Biogeosciences, 11(24), 7305–7329, doi:10.5194/bg-11-7305-2014, 2014.

Li, F., Bond-Lamberty, B. and Levis, S.: Quantifying the role of fire in the Earth system – Part 2: Impact on the net carbon balance of global terrestrial ecosystems for the 20th century, Biogeosciences, 11(5), 1345–1360, doi:10.5194/bg-11-1345-2014, 2014.

Li, F., Levis, S. and Ward, D. S.: Quantifying the role of fire in the Earth system – Part 1: Improved global fire modeling in the Community Earth System Model (CESM1), Biogeosciences, 10(4), 2293–2314, doi:10.5194/bg-10-2293-2013, 2013.

Liu, H. and Randerson, J. T.: Interannual variability of surface energy exchange depends on stand age in a boreal forest fire chronosequence, J. Geophys. Res., 113(G1), G01006, doi:10.1029/2007JG000483, 2008.

Liu, J., Wang, B., Cane, M. A., Yim, S.-Y.and Lee, J.-Y.: Divergent global precipitation changes induced by natural versus anthropogenic forcing, Nature, 493(7434), 656–659, doi:10.1038/nature11784, 2013.

Luyssaert, S., Ciais, P., Piao, S. L., Schulze, E.-D., Jung, M., Zaehle, S., Schelhaas, M. J., Reichstein, M., Churkina, G., Papale, D., Abril, G., Beer, C., Grace, J., Loustau, D., Matteucci, G., Magnani, F., Nabuurs, G. J., Verbeeck, H., Sulkava, M., Van Der WERF, G. R., Janssens, I. A. and Team, members of the C.-I. S.: The European carbon balance. Part 3: forests, Global Change Biol., 16(5), 1429–1450, doi:10.1111/j.1365-2486.2009.02056.x, 2010.

Mack, M. C., Bret-Harte, M. S., Hollingsworth, T. N., Jandt, R. R., Schuur, E. A. G., Shaver, G. R. and Verbyla, D. L.: Carbon loss from an unprecedented Arctic tundra wildfire, Nature, 475(7357), 489–492, doi:10.1038/nature10283, 2011.

Magi, B. I., Rabin, S., Shevliakova, E. and Pacala, S.: Separating agricultural and non-agricultural fire seasonality at regional scales, Biogeosciences, 9(8), 3003–3012, doi:10.5194/bg-9-3003-2012, 2012.

Marlier, M. E., DeFries, R., Pennington, D., Nelson, E., Ordway, E. M., Lewis, J., Koplitz, S. N. and Mickley, L. J.: Future fire emissions associated with projected land use change in Sumatra, Glob. Change Biol., 21(1), 345–362, doi:10.1111/gcb.12691, 2015.

Meehl, G. A. and Washington, W. M.: El Niño-like climate change in a model with increased atmospheric CO2 concentrations, Nature, 382(6586), 56–60, doi:10.1038/382056a0, 1996.

Mouillot, F. and Field, C. B.: Fire history and the global carbon budget: a 1 degrees x 1 degrees fire history reconstruction for the 20th century, Global Change Biol., 11, 398–420, doi:10.1111/j.1365-2486.2005.00920.x, 2005.

Page, S. E., Siegert, F., Rieley, J. O., Boehm, H.-D. V., Jaya, A. and Limin, S.: The amount of carbon released from peat and forest fires in Indonesia during 1997, Nature, 420(6911), 61–65, doi:10.1038/nature01131, 2002.

Peterson, D. L. and Ryan, K. C.: Modeling postfire conifer mortality for long-range planning, Environ. Manage., 10, 797–808, doi:10.1007/BF01867732, 1986.

Pettinari M. L. and Chuvieco E.: Development of a global fuel map using the Fuel Characteristic Classification System. To be submitted to Glob. Ecol. Biogeogr..

Piao, S., Sitch, S., Ciais, P., Friedlingstein, P., Peylin, P., Wang, X., Ahlström, A., Anav, A., Canadell, J. G., Cong, N., Huntingford, C., Jung, M., Levis, S., Levy, P. E., Li, J., Lin, X., Lomas, M. R., Lu, M., Luo, Y., Ma, Y., Myneni, R. B., Poulter, B., Sun, Z., Wang, T., Viovy, N., Zaehle, S. and Zeng, N.: Evaluation of terrestrial carbon cycle models for their response to climate variability and to CO2 trends, Global Change Biol., 19(7), 2117–2132, doi:10.1111/gcb.12187, 2013.

Podgorny, I. A., Li, F. and Ramanathan, V.: Large Aerosol Radiative Forcing due to the 1997 Indonesian Forest Fire, Geophys. Res. Lett., 30(1), 1028, doi:10.1029/2002GL015979, 2003.

Prentice, I. C., Kelley, D. I., Foster, P. N., Friedlingstein, P., Harrison, S. P. and Bartlein, P. J.: Modeling fire and the terrestrial carbon balance, Global Biogeochem. Cycles, 25, GB3005, doi:201110.1029/2010GB003906, 2011.

Prudhomme, C., Giuntoli, I., Robinson, E. L., Clark, D. B., Arnell, N. W., Dankers, R., Fekete, B. M., Franssen, W., Gerten, D., Gosling, S. N., Hagemann, S., Hannah, D. M., Kim, H., Masaki, Y., Satoh, Y., Stacke, T., Wada, Y. and Wisser, D.: Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment, Proc. Natl. Acad. Sci. U.S.A., 201222473, doi:10.1073/pnas.1222473110, 2013.

Pyne, S. J., Andrews, P. L., and Laven, R. D.: Introduction to wildland fire, 2 edition, Wiley, New York, 769 pp., 1996.

Le Quéré, C., Andres, R. J., Boden, T., Conway, T., Houghton, R. A., House, J. I., Marland, G., Peters, G. P., van der Werf, G. R., Ahlström, A., Andrew, R. M., Bopp, L., Canadell, J. G., Ciais, P., Doney, S. C., Enright, C., Friedlingstein, P., Huntingford, C., Jain, A. K., Jourdain, C., Kato, E., Keeling, R. F., Klein Goldewijk, K., Levis, S., Levy, P., Lomas, M., Poulter, B., Raupach, M. R., Schwinger, J., Sitch, S., Stocker, B. D., Viovy, N., Zaehle, S. and Zeng, N.: The global carbon budget 1959–2011, Earth Syst. Sci. Data, 5(1), 165–185, 2013.

Randerson, J. T., Chen, Y., van der Werf, G. R., Rogers, B. M. and Morton, D. C.: Global burned area and biomass burning emissions from small fires, J. Geohys. Res., B, 117(G4), G04012, doi:10.1029/2012JG002128, 2012.

Rocha, A. V. and Shaver, G. R.: Postfire energy exchange in arctic tundra: the importance and climatic implications of burn severity, Global Change Biol., 17(9), 2831–2841, doi:10.1111/j.1365-2486.2011.02441.x, 2011.

Rogers, A.: The use and misuse of V c,max in Earth System Models, Photosynth Res, 119(1-2), 15–29, doi:10.1007/s11120-013-9818-1, 2014.

Ropelewski, C. F. and Halpert, M. S.: Global and Regional Scale Precipitation Patterns Associated with the El Niño/Southern Oscillation, Mon. Wea. Rev., 115(8), 1606–1626, doi:10.1175/1520-0493(1987)115<1606:GARSPP>2.0.CO;2, 1987.

Ropelewski, C. F. and Halpert, M. S.: Quantifying Southern Oscillation-Precipitation Relationships, J. Climate, 9(5), 1043–1059, doi:10.1175/1520-0442(1996)009<1043:QSOPR>2.0.CO;2, 1996.

Rothermel, R. C.: A mathematical model for predicting fire spread in wildland fuels, Res. Pap. INT-115, Ogden, UT: U.S. Department of Agriculture, Intermountain Forest and Range Experiment Station, 40 pp., available at: http://www.fs.fed.us/rm/pubs_int/int_rp115.pdf (last access: 30 September 2014), 1972.

Roy, D. P., Boschetti, L., Justice, C. O. and Ju, J.: The collection 5 MODIS burned area product -- Global evaluation by comparison with the MODIS active fire product, Remote Sensing of Environment, 112(9), 3690–3707, doi:16/j.rse.2008.05.013, 2008.

Schimel, D. and Baker, D.: Carbon cycle: The wildfire factor, Nature, 420(6911), 29–30, doi:10.1038/420029a, 2002.

Seiler, W. and Crutzen, P. J.: Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning, Clim. Change, 2(3), 207–247, doi:10.1007/BF00137988, 1980.

Staver, A. C., Archibald, S. and Levin, S. A.: The Global Extent and Determinants of Savanna and Forest as Alternative Biome States, Science, 334(6053), 230–232, doi:10.1126/science.1210465, 2011.

Tansey, K., Grégoire, J.-M., Defourny, P., Leigh, R., Pekel, J.-F., van Bogaert, E. and Bartholomé, E.: A new, global, multi-annual (2000–2007) burnt area product at 1 km resolution, Geophys. Res. Lett., 35(1), doi:10.1029/2007GL031567, 2008.

Thonicke, K., Spessa, A., Prentice, I. C., Harrison, S. P., Dong, L. and Carmona-Moreno, C.: The influence of vegetation, fire spread and fire behaviour on biomass burning and trace gas emissions: results from a process-based model, Biogeosciences, 7(6), 1991–2011, 2010.

Timmermann, A., Oberhuber, J., Bacher, A., Esch, M., Latif, M. and Roeckner, E.: Increased El Niño frequency in a climate model forced by future greenhouse warming, Nature, 398(6729), 694–697, doi:10.1038/19505, 1999.

Tosca, M. G., Randerson, J. T., Zender, C. S., Flanner, M. G. and Rasch, P. J.: Do biomass burning aerosols intensify drought in equatorial Asia during El Niño?, Atmos. Chem. Phys., 10(8), 3515–3528, doi:10.5194/acp-10-3515-2010, 2010.

Turetsky, M. R., Kane, E. S., Harden, J. W., Ottmar, R. D., Manies, K. L., Hoy, E. and Kasischke, E. S.: Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands, Nature Geosci, 4(1), 27–31, doi:10.1038/ngeo1027, 2011.

Ward, D. S., Kloster, S., Mahowald, N. M., Rogers, B. M., Randerson, J. T. and Hess, P. G.: The changing radiative forcing of fires: global model estimates for past, present and future, Atmos. Chem. Phys., 12(22), 10857–10886, doi:10.5194/acp-12-10857-2012, 2012.

Van der Werf, G. R., Dempewolf, J., Trigg, S. N., Randerson, J. T., Kasibhatla, P. S., Giglio, L., Murdiyarso, D., Peters, W., Morton, D. C., Collatz, G. J., Dolman, A. J. and DeFries, R. S.: Climate regulation of fire emissions and deforestation in equatorial Asia, Proc. Natl. Acad. Sci. U.S.A., 105(51), 20350–20355, doi:10.1073/pnas.0803375105, 2008.

Van der Werf, G. R., Morton, D. C., DeFries, R. S., Olivier, J. G. J., Kasibhatla, P. S., Jackson, R. B., Collatz, G. J. and Randerson, J. T.: CO2 emissions from forest loss, Nature Geosci, 2(11), 737–738, doi:10.1038/ngeo671, 2009.

Van der Werf, G. R., Randerson, J. T., Collatz, G. J., Giglio, L., Kasibhatla, P. S., Arellano, A. F., Olsen, S. C. and Kasischke, E. S.: Continental-Scale Partitioning of Fire Emissions During the 1997 to 2001 El Niño/La Niña Period, Science, 303(5654), 73–76, doi:10.1126/science.1090753, 2004.

Van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Kasibhatla, P. S. and Arellano Jr., A. F.: Interannual variability in global biomass burning emissions from 1997 to 2004, Atmos. Chem. Phys., 6(11), 3423–3441, 2006.

Van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y. and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), Atmos. Chem. Phys., 10(23), 11707–11735, doi:10.5194/acp-10-11707-2010, 2010.

Venevsky, S., Thonicke, K., Sitch, S., and Cramer, W.: Simulating fire regimes in human-dominated ecosystems: Iberian Peninsula case study, Glob. Change Biol., 8, 984–998, doi:10.1046/j.1365-2486.2002.00528.x, 2002.

Westerling, A. L., Turner, M. G., Smithwick, E. A. H., Romme, W. H. and Ryan, M. G.: Continued warming could transform Greater Yellowstone fire regimes by mid-21st century, Proc. Natl. Acad. Sci. U.S.A., 201110199, doi:10.1073/pnas.1110199108, 2011.

Wilson, R. A. J.: A reexamination of fire spread in free-burning porous fuel beds [Wildland fuels, forest fire management, model], USDA Forest Service Research Paper INT (USA), available at: http://agris.fao.org/agris-search/search.do?f=1983/US/US83048.xml;US8236661 (last access; 15 February 2014), 1982.

Wirth, C.: Fire Regime and Tree Diversity in Boreal Forests: Implications for the Carbon Cycle, in Forest Diversity and Function, edited by D. M. Scherer-Lorenzen, P. D. C. Körner, and P. D. E.-D. Schulze, pp. 309–344, Springer Berlin Heidelberg. [online] Available from: http://link.springer.com/chapter/10.1007/3-540-26599-6_15 (Accessed 17 November 2014), 2005.

Yue, C., Ciais, P., Cadule, P., Thonicke, K., Archibald, S., Poulter, B., Hao, W. M., Hantson, S., Mouillot, F., Friedlingstein, P., Maignan, F., and Viovy, N.: Modelling fires in the terrestrial carbon balance by incorporating SPITFIRE into the global vegetation model ORCHIDEE – Part 1: Simulating historical global burned area and fire regime, Geosci. Model Dev. Discuss., 7, 2377-2427, doi:10.5194/gmdd-7-2377-2014, 2014.

Zhao, M. and Running, S. W.: Drought-Induced Reduction in Global Terrestrial Net Primary Production from 2000 Through 2009, Science, 329(5994), 940–943, doi:10.1126/science.1192666, 2010.

Tables and figures

Table 1 Comparison of simulated and GFED3.1 fire carbon emissions, burned area and total fuel consumption (TFC, including consumption of surface dead litter or organic soil, and live biomass) for different regions averaged over 1997–2009. The locations of the GFED regions are mapped in Fig. S5, the abbreviations expanded in the caption to Fig. 4. The last three columns provide a qualitative indication of the error in simulated carbon emissions and its attribution to those of burned area and TFC. To obtain the qualitative error information, the ratio of simulated value to GFED3.1 is compared to the coefficient of variation (CV) of the corresponding GFED3.1 value as following:

= , no error, if the ratio is within (1-CV, 1+CV);

+, overestimated, if the ratio falls in (1+CV, 3);

++, moderately overestimated, if the ratio falls in (3,10);

+++, highly overestimated, if the ratio is bigger than 10;

-, underestimated, if the ratio falls in (0.3, 1-CV);

--, moderately underestimated, if the ratio falls in (0.1, 0.3)

The CV for annual emissions and burned area by GFED3.1 data was calculated using the annual time series. Total fuel consumption data for GFED3.1 were obtained from Table 4 of van der Werf et al. (2010) and an arbitrary CV of 0.3 was adopted.

Region	Emissions (Tg C yr^{-1})		Burned area ($Mha\ yr^{-1}$)		Total fuel consumption (g C $m^{-2}$of BA)		Emission error	BA error	TFC error
	GFED3.1	ORC	GFED3.1	ORC	GFED3.1	ORC			
BONA	54	45	2.1	3.3	2662	1385	=	=	-
TENA	9	96	1.5	18.5	627	514	+++	+++	=
CEAM	20	29	1.4	4.1	1489	714	=	+	-
NHSA	22	79	2.1	5.8	1007	1351	++	+	+
SHSA	272	369	20	35.7	1311	1035	=	+	=
EURO	4	13	0.7	1.5	667	874	++	+	+
MIDE	2	24	0.9	8.8	198	278	+++	+++	+
NHAF	480	680	129	58.7	377	1159	+	-	++
SHAF	556	331	125	34.1	448	969	-	--	+

BOAS	128	61	6.6	3.9	1979	1589	-	-	=
SEAS	103	40	14	4.1	253	969	-	-	++
CEAS	35	161	7	41.4	1459	388	++	++	--
EQAS	181	2	1.8	0.1	9500	1559	--	--	--
AUST	133	174	52	15.6	259	1118	=	-	++
Global*	1999	2104	364	236	549	891	=	-	+

* For GFED3.1 data, burned area and emissions from all types of fires are included, i.e., forest fire, grassland fire, woodland fire, agricultural fire, deforestation and peatland fire.

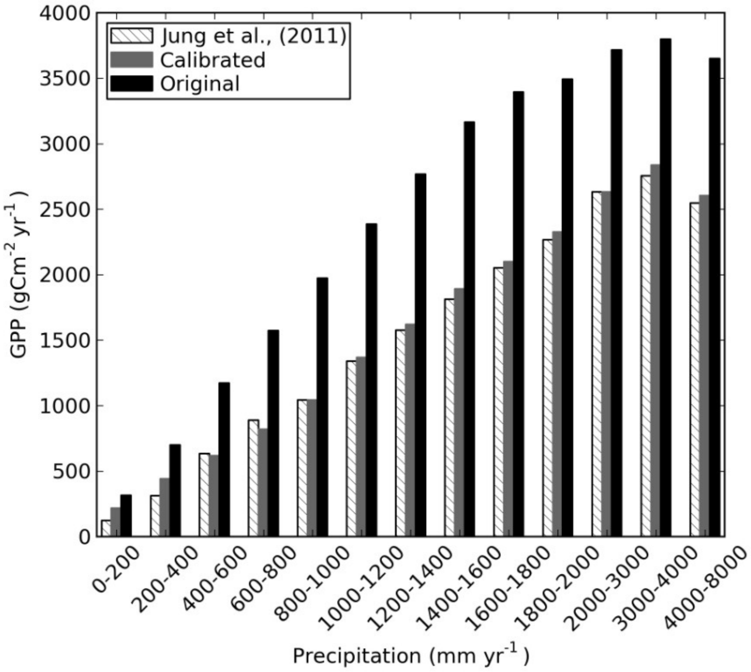

Fig. 1 Annual GPP as a function of annual precipitation according to Jung et al. (2011) (dashed bar), model simulation before (black bar) and after calibration (grey bar).

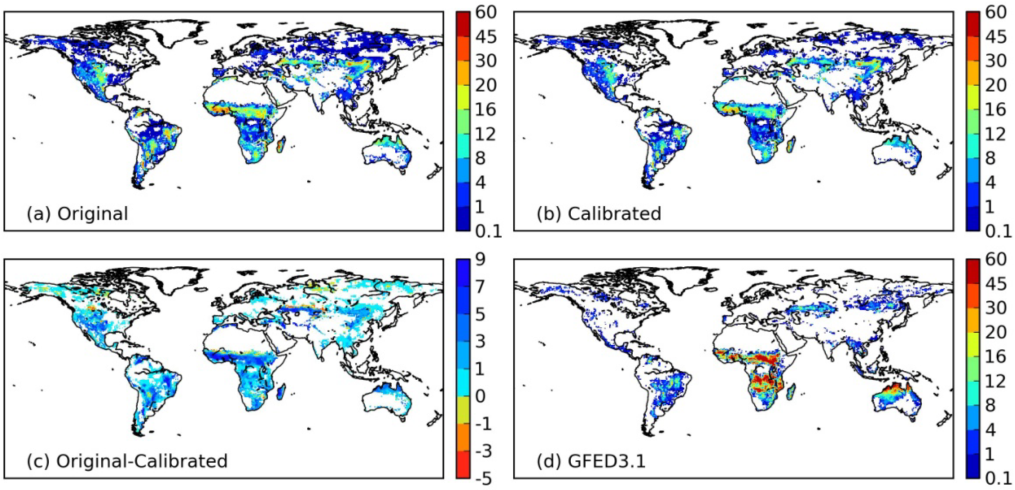

Fig. 2 Simulated mean annual burned fraction (%) for 1997–2009 for (a) original and (b) calibrated model productivity. The change in burned fraction (original - calibrated) is shown in panel (c), and the burned fraction by GFED3.1 data is shown in panel (d).

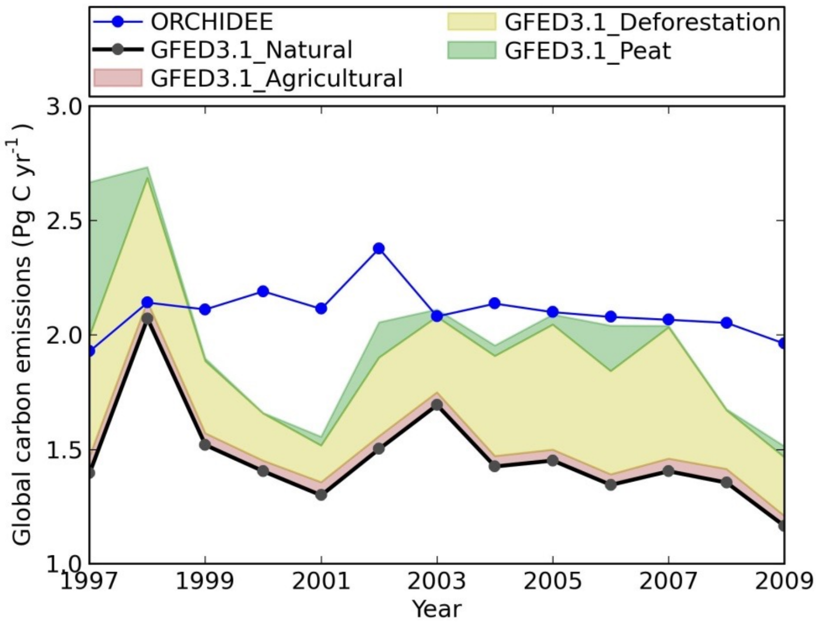

Fig. 3 Annual global fire carbon emissions for 1997–2009 simulated by ORCHIDEE (blue), and from the GFED3.1 data. Carbon emissions from natural sources (forest fire, grassland fire, and woodland fire) are shown as the black solid line. Carbon emissions from agricultural fire, deforestation fire and peat fire (which are not explicitly simulated in ORCHIDEE) are shown as shaded areas stacked on top of GFED3.1 natural source fire carbon emissions.

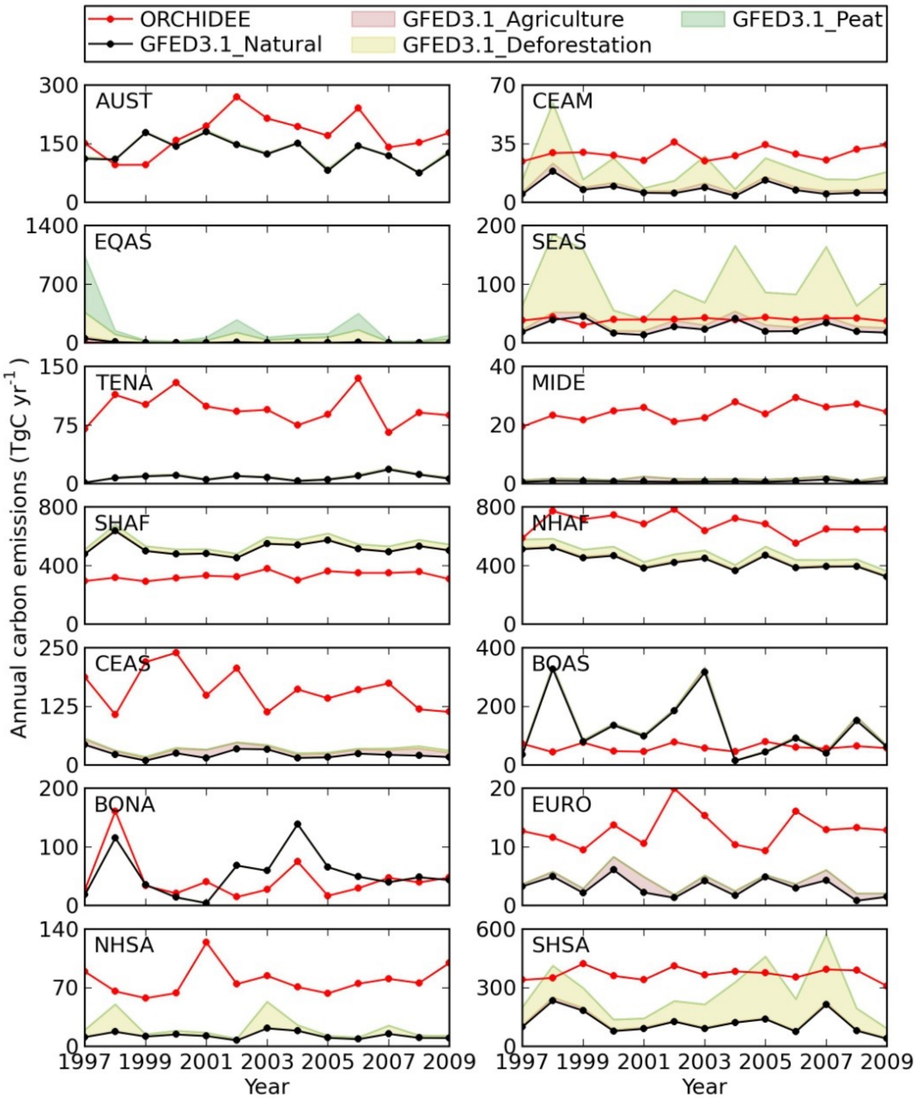

Fig. 4 Annual fire carbon emissions simulated by ORCHIDEE and from the GFED3.1 data for 1997–2009 for the 14 different GFED regions. The 14 GFED regions are, BONA: Boreal North America; TENA: Temperate North America; CEAM: Central America; NHSA: Northern Hemisphere South America; SHSA: Southern Hemisphere South America; EURO: Europe; MIDE: Middle East; NHAF: Northern Hemisphere Africa; SHAF: Southern Hemisphere Africa; BOAS: Boreal Asia; CEAS: Central Asia; SEAS: Southeast Asia; EQAS: Equatorial Asia; AUST: Australia and New Zealand. Refer to Fig. S5 for their distributions.

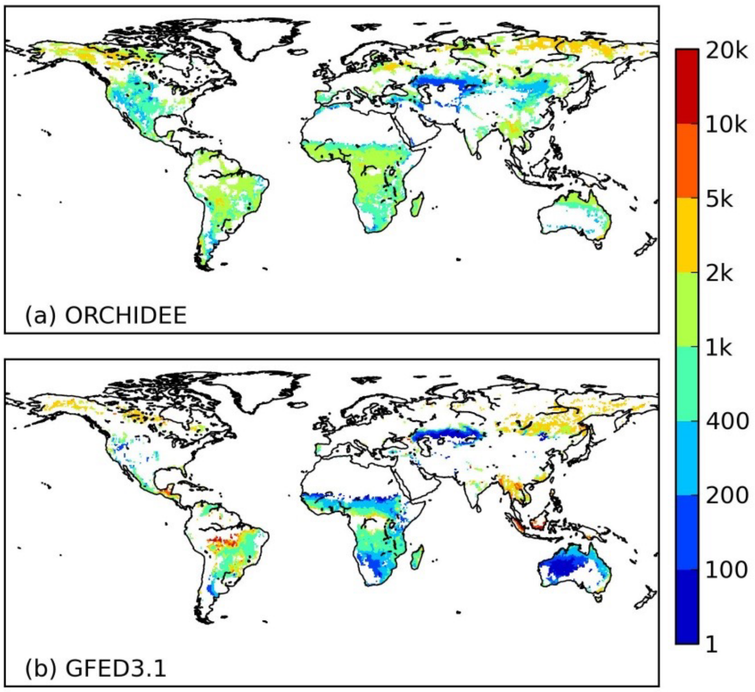

Fig. 5 Fuel consumption (g C per m^2 of area burned) averaged over 1997–2009 by (a) ORCHIDEE simulation and (b) the GFED3.1 data.

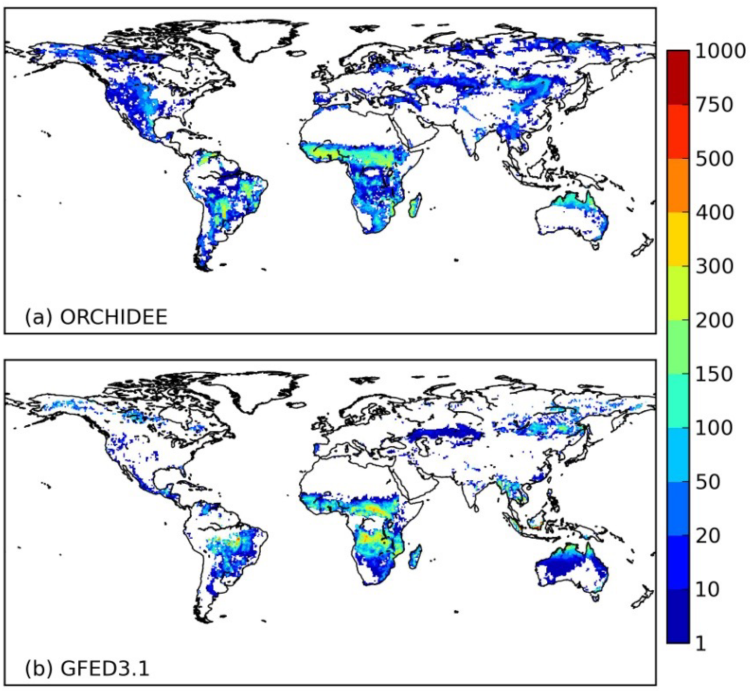

Fig. 6 Mean annual carbon emissions (g C m^{-2}) for 1997–2009 by (a) ORCHIDEE simulation and (b) the GFED3.1 data, based on the whole grid cell area included both burned and unburned parts.

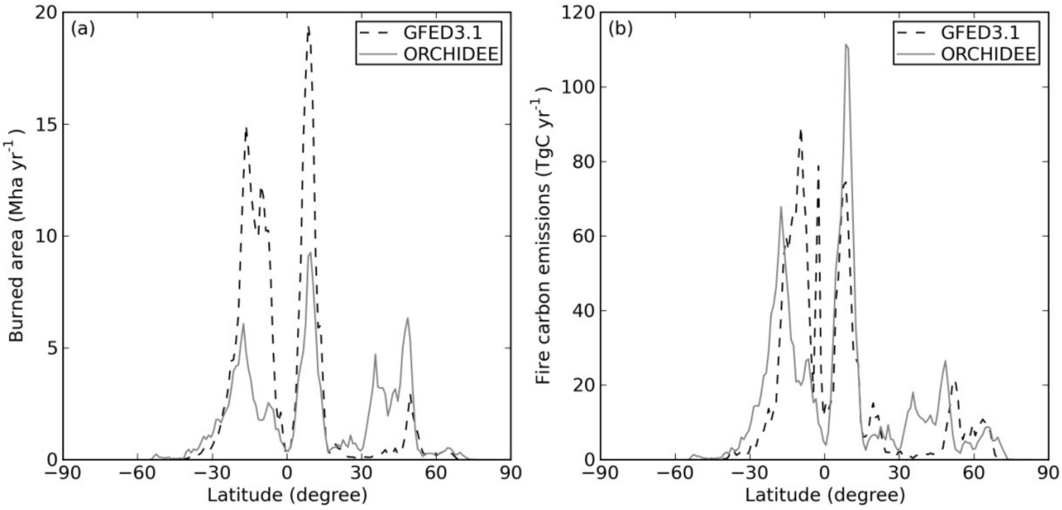

Fig. 7The latitudinal distribution of (a) burned area and (b) fire carbon emissions as simulated by ORCHIDEE (grey solid line) and by the GFED3.1 data (black dashed line).

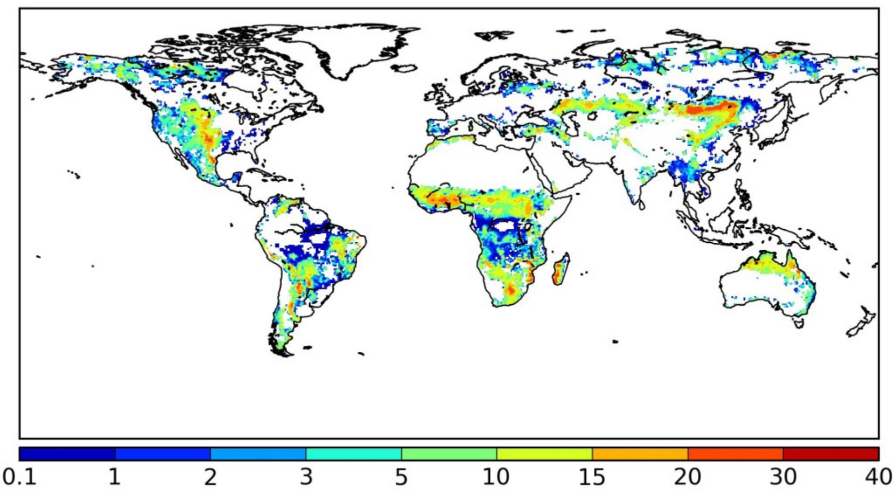

Fig. 8 The fire carbon emissions as percentage (%) of net primary production (NPP) for 2003–2012.

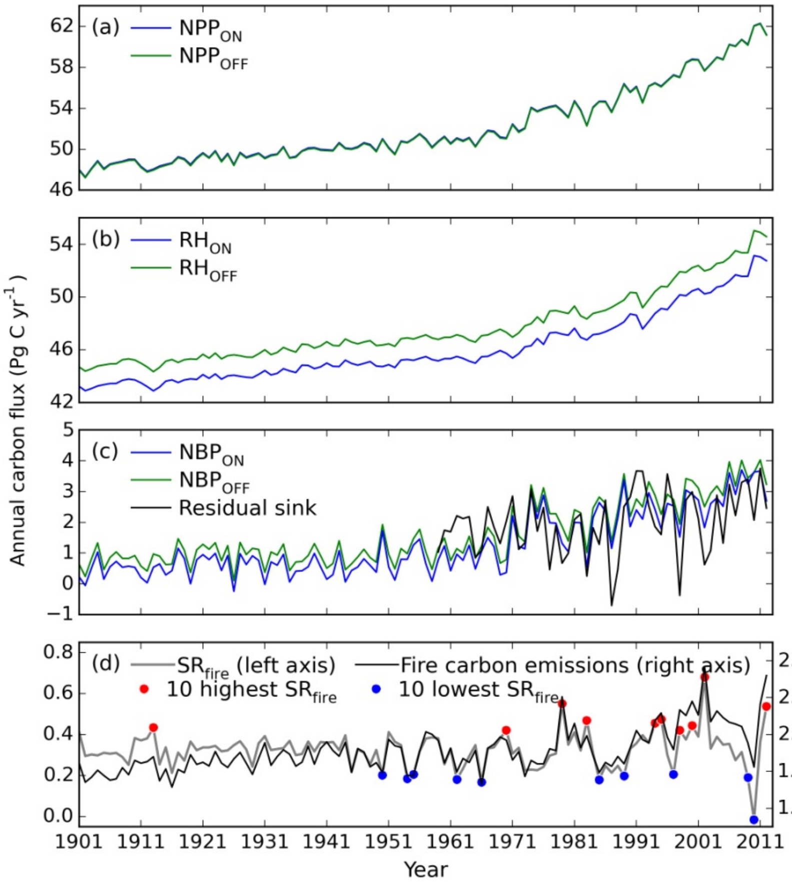

Fig. 9 Different components of global carbon fluxes for fireON and fireOFF simulations. The carbon fluxes are (a) NPP; (b) heterotrophic respiration (RH); (c) NBP and the residual land sink as reported by Le Quéré et al. (2013); and (d) The NBP reduction by fires (SR_{fire} = NBP_{OFF} - NBP_{ON}, in grey, left vertical axis) and fire carbon emissions (black, right vertical axis).

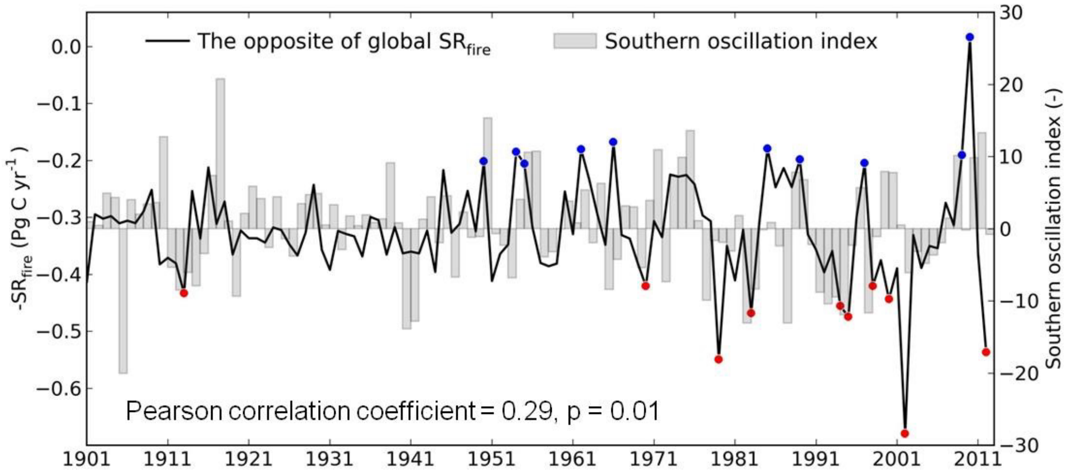

Fig. 10 The fire-induced sink reduction (left vertical axis, -SR_{fire}) and its correlation with the Southern Oscillation Index (SOI, right vertical axis) which is an indicator for the El Niño Southern Oscillation (ENSO) climate oscillation. The red dots indicate the ten highest SR_{fire} years and the blue dots indicate the ten lowest SR_{fire} years. Note that the left vertical axis shows the

opposite of SR_{fire}.

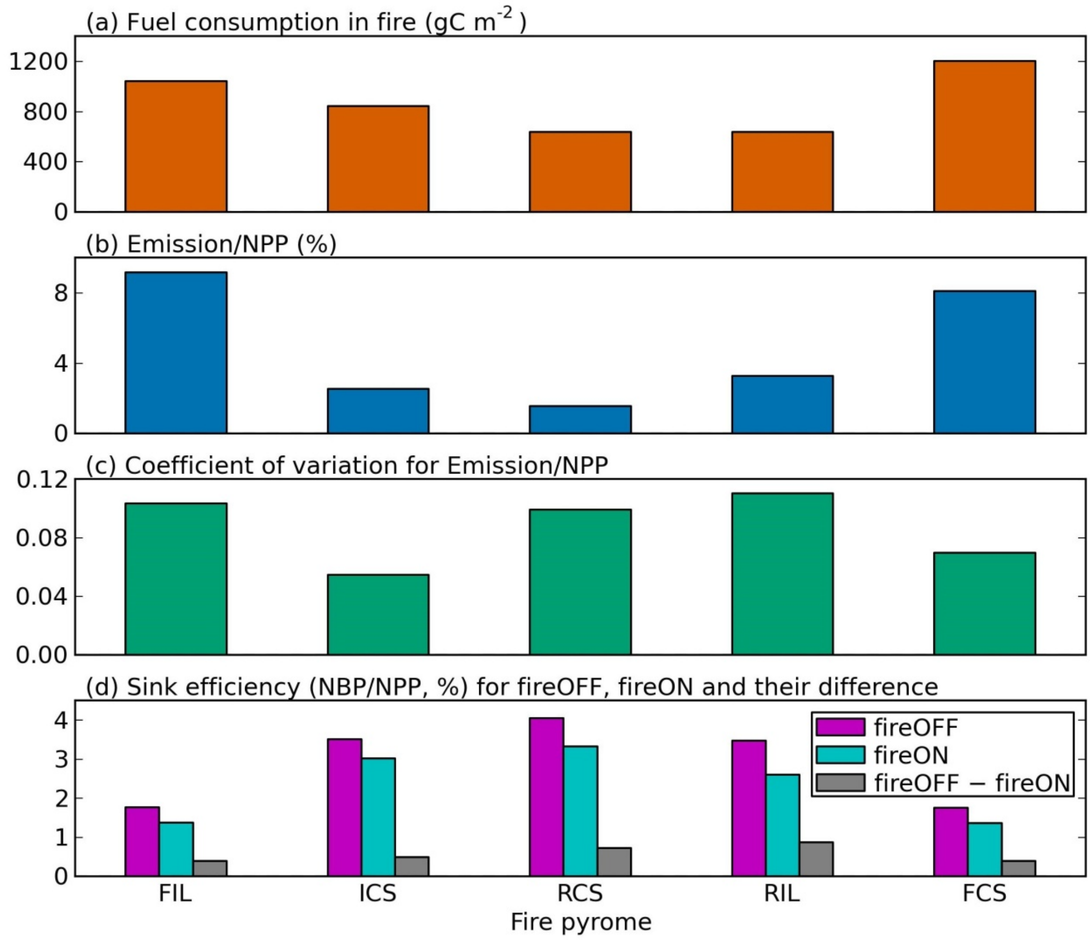

Fig. 11 Characteristics of different fire pyromes (defined as by Archibald et al., 2013) in terms of the role of fires in the terrestrial carbon balance. (a) Fuel consumption in fire; (b) Emissions as percentage of NPP; (c) Coefficient of variation for the ratio of emissions against NPP; and (d) Sink efficiencies (i.e., NBP/NPP) for fireOFF and fireON simulations and their difference. All variables are shown for 1901–2012 except the fuel carbon consumption which is averaged over 2003–2012. The five fire pyromes are: FIL, Frequent–Intense–Large; ICS, Intermediate–Cool–Small; RCS, Rare–Cool–Small; RIL, Rare–Intense–Large; FCS, Frequent–Cool–Small. Refer to Fig. S2 for their spatial distributions.