We thank the reviewers for their detailed and constructive comments, which strongly helped to improve the manuscript. We included additional analysis on the correlation between burned fraction and tree cover and on the increase of maximum tree cover with increasing precipitation. We hope our replies to the reviewer comments and the modifications will make the manuscript suitable for publication in biogeosciences. Our reponses are inserted below the reviewer comments in italics.

1 Review 1

General Comments:
Reviewer summary: The manuscript presents results from multi-variate comparisons between a simple fire model and complex fire model within JSBACH against those of remote sensing datasets for tree cover, grass cover, and burned fraction for regions within the tropics. The work finds that the resolution of the remote sensing datasets is important for setting precipitation limits on tree cover and burned fraction classifi- cations. The fire models capture broad spatial patterns, but overall the complex fire model has improved performance. The analysis was completed for continental sub- sets and with and without preindustrial land use. Given the results the authors suggest C1 improving the drought response of vegetation, including more complex bark thickness for trees, and a representation of size-structure. The multi-variate analysis used here better identifies model-data mismatches to model processes.
Article contribution and overall impact: This study highlights the challenges of simula- tion of vegetation-fire interactions across the tropics. Strong climate vegetation rela- tionships and a closely interacting fire regime make the vegetation state of this region difficult to simulate. The manuscript does a good job of presenting the challenges of capturing vegetation and fire in the tropics with simulation and with remote sensing datasets. The discussion would benefit from a more detailed description of the con- nections between recommended improvements and deficiencies of the simulations, as well as inclusion of more references. Please update the discussion to include a ref- erence back to the figure or table being discussed (some of these are highlighted in detail comments). Specifically, more detailed discussion of size-structure and its im- portance as a mechanism for tree survival in fire prone regions should be included. A key component of the mortality of woody vegetation to fire is its size at the time of fire and the ability to accumulate size between fires. This is central to the work of many of W. Hoffman's papers in the region (Hoffman et al 2003, Hoffman et al 2009, Hoffman et al 2012). This type of work should be referenced as well as important differences between the continents in terms of vegetation survival from fire.

1) We thank the reviewer for identifying this lack of details. We extended the discussion to improve the connection between improvements and deficiencies of simulated patterns including the recommended inclusion of more references to literature but also to the figures and table in the results section.

Detailed comments:
Page 6 line 15: Are burned area and burned fraction the same?

2) Burned area refers to the area, burned fraction to the fraction of the grid cell. It therefore is the same parameter but with a different unit. We change the burned area to burned fraction here, as the burned fraction is displayed in the figure to avoid confusion.

Page 7 line 12: "stronger relationship between low tree cover and high fire occurrence than observations" Explain this in more detail. By what measure and for which figure/table?

3) We modified the paragraph to explain it in more detail and refer to figure 4 and table 1. We also performed an additional analysis and include the correlation between burned fraction and tree cover in table 1 to quantify this strength of the relationship.
"Models and observations generally agree on the absence of fire for very high tree cover (>0.8) and on the decrease of burned fraction for mean annual precipitation decreasing below 1000 mm. However for regions with tree cover < 0.8 and mean annual

precipitation > 1000 mm we find strong differences. JSBACH-SPITFIRE shows a strong negative Spearman rank correlation between burned fraction and tree cover, the observations show a weak negative correlation, and JSBACH-standard shows a positive correlation (Table 1). This can also be seen in Figure 4 where for the JSBACH-SPITFIRE simulation the highest burned fractions (> 50% of grid cells year^{-1}) are found in Africa for the lowest tree covers (0.1) and for precipitation between 1000-2000 mm year^{-1}. JSBACH-standard in many grid cells shows low fire occurrence for low tree cover, especially for South America (Figure 4), these grid cells have a high fraction of crops or pasture, which both are excluded from burning in JSBACH-standard (in SPITFIRE only crops are excluded). The observations (also Figure 4) show highest values of the burned fraction for tree cover values up to 0.3 for MODIS and up to 0.5 for LANDSAT."

Page 9 line 6: Why use the preindustrial land use? The observation datasets are for the period of 1996-2005.

4) The preindustrial state is a state with low influence of land use, the comparison with the historical simulation therefore indicates the effect land use has on the climate-vegetation-fire relationships. We add two sentences in the beginning of the paragraph to explain the purpose:
"The simulation with preindustrial land use represents a state with low influence of land use change. The comparison to the historical simulation allows to assess the influence of land use change since 1850."
We also include a description of the changes in statistical parameters listed in table 1:
"The impact of fire on tree cover as quantified by the Spearman rank correlation between burned fraction and tree cover is higher for the simulation with preindustrial land use (Table 1). Land use change did not affect the rank correlation between precipitation and temperature. The precipitation range for 80% of the burned area is only slightly narrower for the simulation including land use change (Table 1). Tree cover, however, is even higher for low precipiation and reaches canopy closure for lower precipitation (Table 1 and Figure 7 compared to Figure 4)."

Page 10 line 4: Update "We here discuss. . ." to "Here we discuss. . ."

5) Updated in the revised manuscript.

Page 10 line 7: Clarify that improvements in the SPITFIRE version cannot improve this mismatch. The standard version does not capture the observations as shown in figure 3.

6) We changed this part (which refers to the mismatch of tree cover in low precipitation areas) to:
"In these dry regions no or only very low burned fractions are observed, and SPITFIRE shows a good response to precipitation while JSBACH-standard already overestimates the burned area (Figure 3). The improved burned area pattern of SPITFIRE did not lead to an improvement in tree cover for these dry regions. It is therefore unlikely that further improvements in burned fraction will improve this model-data mismatch, satellite data however indicate that the intensity of fires increases in these regions and might help to explain the disappearance of trees (Hantson et al., 2017). The mechanisms however are not sufficiently understood to be included in a model."

Page 11 line 3: update "too high tree cover" to "excessive tree cover",
and
Page 11 line 5: update "too high dominance" to "excessive dominance"

7) Done as suggested, we also change "too high" to "excessive" in the abstract.

Page 11 line 6-7: Explain how saplings being inferior to grasses would improve the representation of tree-grass competition? How would these saplings alter the resulting tree cover in areas where grasses exist? Are there processes in the model that would need to be added to include grass suppression of saplings?

8) Whether or not the inclusion of saplings would improve the representation of tree cover is certainly a matter of the exact implementation and model tuning. Answers to these detailed questions would therefore be highly speculative. We are therefore careful with our statements and add:
"Including this mechanism could improve the balance between tree and grass cover, but it could also reduce the establishment rate of trees and, therefore, the tree cover in the dry regions with excessive tree cover. Including a PFT-specific rooting depth of vegetation would be an important extension of the model to improve the competition for water between grasses, saplings and adult trees." In the end of the paragraph on model improvements we also add: "How exactly these plausible modifications would change the patterns of tree cover, fire and their relation to climate likely strongly depends on the exact parameterization and needs to be tested with stepwise model development and factorial simulations." To make sure readers understand that these are only suggestions and that they first need to be tested to understand how exactly they change the simulation outcome.

Page 11 line 8-9: Include the figure that this relationship is referring to "higher burned fraction and lower tree cover for open canopies, however it is not found in the observations." Is this for figure 4? Also specify for what regions, as they are not consistent.

9) We updated the sentence with references to figures:
The absence of fire for closed canopies is captured well by JSBACH-SPITFIRE, the modelled strong relationship between higher burned fraction and lower tree cover for open canopies (Figure 4, with the exception of Australia, Table 1), however, is not found in the observations (Figure 2,4). See also reply 3.

Page 12 line 1: Explain how increased bark thickness would be implemented in the model. Include discussion of the relationship between bark thickness and size- structure of trees, and species or regional variability in bark thickness characteristics, and how this might be accounted for in the model.

10) There are several ways to increase bark thickness, the first would be to modify the PFT specific bark thickness which depends on the tree biomass. Bark thickness could also increase according to previously burned area, assuming tree invest more in bark in regions with high fire occurrence. We modified the existing paragraph to:
"Bark thickness is a key property of trees for the fire-related mortality. In JSBACH-SPITFIRE bark thickness is PFT specific and depends on the biomass. The adaptation of trees to frequent fires by increased bark thickness, and therefore higher resistance of trees to fire (Pellegrini et al., 2017) would increase the tree cover in regions with high burned fraction. This could be implemented in the model with more specific PFTs or by modifying the bark thickness according to the fire regime. Kelley and Harrison (2014) included bark thickness as an adaptive trait in the LPX model, which increased and improved the tree cover for Australia. Resprouting is another important mechanism that changes the balance between mortality and recovery and also leads to an increase in tree cover in fire affected areas in a modelling study (Kelley and Harrison, 2014)."
see also reply 45

Page 12 line 4: "This feedback is included. . .but might be too weak." Support this statement with more detail. What information indicates that the feedback is too weak? Is this true for all regions? Which figures lead to this assertion?

11) This still refers to the correlation between burned fraction and tree cover and the highest burned fractions for rather high tree cover in the observations. We suggest two possibilities of what could cause the higher correlation in the model, adaptation of bark thickness to fire regime or the feedback between fuel load and tree mortality. We slightly changed the sentence to clarify.

Page 12 line 5-6: ". . .long-lived adult tree state could increase the survival of trees." How long do trees live in JSBACH? Provide some background on existing parameter- ization of tree life span and mortality mechanisms to support this statement. Include discussion of Hoffman's work on the 'fire-trap' within savanna systems.

12) We include discussion on the general priciples proposed and supported by the work of Hoffmann, however his studies do not offer an explanation why the highest burned fractions are observed for rather high tree cover, which is the main surprise in

the comparison here and the subject of the paragraph. The general principles dealt with in the work of Hoffmann are included in the model already. We include his work now in the discussion: "The absence of fire for closed canopies is captured well by JSBACH-SPITFIRE, the modelled strong relationship between higher burned fraction and lower tree cover for open canopies (Figure 4, with the exception of Australia, Table 1), however, is not found in the observations (Figure 2, 4,Table 1). Many general processes determining the savanna-forest boundary are included in the JSBACH-SPITFIRE model: Increased tree cover leads to a suppression of fire by excluding grasses, higher flammability of grasses leads to increases in fire occurrence with increasing grass biomass (Hoffmann et al., 2012). In JSBACH-SPITFIRE bark thickness is PFT specific and depends on the biomass. Tropical trees are represented by two PFTs one of them has a lower sensitivity to fire due to a higher bark thickness and a higher stem leading to a lower probability of crown scorch. This is also observed in field studies where savanna species show a higher ratio of bark thickness to stem diameter (Hoffmann et al., 2003). "

Page 12 line 7: "For Australia. . .for both fire models is strong." Include the figure this is referencing. Figure 4?

13) Yes, the reference to figure 4 is included now.

Page 13 line 3: Update to "The rank correlation. . .compared to model outputs (Table 1)." Include the reference to Table 1.

14) We included the reference to the table and updated the sentence.

Page 13 -14 line 1: "adapts to changes in climate with usually PFT specific time scales." What does this mean? Are there variable PFT longevity within simulation?

15) Changes in PFT distributions are not instantanious the response of vegetation to any climate change is therefore delayed and the delay depends on the PFT specific time scale. We change the sentence to "constant PFT specific time scales".

Page 14 line 1-2: Include references to examples of DGVMs which include human dimensions.

16) most of the DGVMs and land surface models do as representing land use change is now really a standard, we therefore do not think that references here are useful. The reference to Hantson et al. (2016) already includes a number of models including human properties. Listing individual model references would only lengthen the references section and would be an arbitrary choice of models.

Page 14 line 2: ". . .population density is a commonly used driver." Driver of what? Ignitions? Land use change? Please clarify.

17) We extend the sentence with: ...commonly used driver for human ignitions and suppression of fires.

Page 14 line 3: Start a new paragraph with the sentence beginning "Our model simulations. . ." and update this sentence to "Our model simulations also show that the modelled climate. . ."

18) This paragraph was rewritten.

Page 14 line 6: Update sentence to ". . .not affected by land use or by the type of fire model. . ."

19) The sentence was removed.

Page 14 line 7: ". . .seasonality that is not resolved by the mean annual precipitation." The model has no seasonal varia-

tion in precipitation and is only using MAP? Please clarify.

20) This part of the discussion was removed. For clarification: the model uses daily precipitation however the comparison was based on MAP."

Page 14 line 8-13: Include discussion of how the results differ due to the use of only preindustrial land use. Qualify the text in this section to clarify that the JSBACH sim- ulations use preindustrial land use and these products use recent land use (Andela et al 2017 uses the past 18 years). Explain why the comparison is still valid.

21) We do not compare the simulations with preindustrial land use to recent satellite products. The decrease in burned area due to land use however is supported by several satellite data analysis. We add a sentence to explain that this is not a direct comparison but refers to the isolation of the effect of land use change: "We seperated the effect of land use change by comparing the historical simulation to a simulation with preindustrial land use. We find that land cover change is influencing the differences in the modelled fire regime between Africa and South America."

Page 14 line 12: "The mechanism behind the reduction due to croplands. . ." Reduction of what? Fire occurrence? Please clarify.

22) We added "burned area" to clarify

Page 14 line 13: ". . .fragmentation of the landscape, which is not explicitly accounted for in the model." Include discussion of how fragmentation affects forests in reality, and how this may be a challenge for models such as JSBACH. Is this an area for potential improvement?

23) Fragmentation can certainly affect forests and for instance their biodiversity in many ways, as the sentence is about the effects of fragmentation on burned area, we indicate how fragmentation affects fire. Fragementation effects on forests are not mentioned here and for a model such as JSBACH we don't see a direct benefit. The fragmentation effects on fire are however very direct as fragmentation often stops fires from spreading. We add:
"Fragmentation of the landscape by for instance roads can act as a fire break and therefore reduce the potential fire size. The exact relationships between humans, land use and vegetation fires are still unknown and therefore not well represented in models."

Page 14 line 17: ". . .spatially varying ignitions." Do ignitions vary temporally?

24) The paragraph is about differences in the spatial patterns between continents. The lightning ignitions vary seasonally and the human ignitions vary annually due to changes in population density. However, as we do not address temporal variability of burned area at all in the manuscript and we only evaluate spatial patterns we do not see a benefit of dicussing the temporal variability.

Page 14 line 18: ". . .these differences in ignitions. . ." Differences between what? One is not spatially varied ignitions? Please clarify.

25) This again refers to the spatial variations in ignitions, we update the sentence to:
"...these spatial differences in ignitions..."

Page 14 line 32-33: Add at the end of the sentence what the values are for the satellite datasets. It is not possible to read them from the figures to compare to this measure of 100 mm and >650 mm per year.

26) We add:
The remote sensing datasets show for Africa an absence of tree cover for precipitation less than ca. 300 mm and canopy closure for 1500 mm year^{-1} in the model resolution (Figure 4).
Page 15 line 6-7: ". . .spatial scale needs to be considered. . ." Add discussion on how increased spatial scale (finer resolution) might improve the model results. Why not perform simulation at 1km similar to the Hirota dataset? Should simulation be finer than 1km? How small of a resolution can you achieve before you see compromised results for simulation?

27) Also here the reviewer asks for answers that can only be adressed by doing simulations in high resolution and testing the influence of model resolution on the simulation results. The only thing we can conclude from our analysis is that some metrics of the comparison depend on the spatial resolution. Such high resolution simulations are also still very computationally intensive and we would not have the necessary computation time available. We now add a sentence to suggest that running the model in higher spatial resolution could improve the performance as the thresholds in the model are closer to the ones found for higher resolution or local scale observations:
"Moreover, as the thresholds found for the model are closer to the ones found for site-level and high resolution satellite datasets the model performance could improve if the spatial resolution of the model is increased."

Page 15 line 11-12: Are there plans to compare to biomass datasets? Identify potential datasets.

28) Including our plans for future work is an uncommon suggestion and we do not see any use of including them. We add references to datasets (SAATCHI, AVITABILE, BACCINI:
"... and pan-tropical datasets are available (Saatchi et al., 2011; Baccini et al., 2012; Avitabile et al., 2016)".

Page 15 line 26-28: "The multivariate comparison helped to . . ." Re-word this sentence. It is not clear what is meant by "too strong effect of fire on tree cover". Split into two sentences to identify problems, and then another to suggest improvements. Clarify where and how increased bark thickness can be included.

29) We changed the sentence as suggested to: "The multivariate comparison revealed a too strong impact of fire on tree cover for gridcells with very high fire occurrence, which leads to too low tree cover. Possible model modifications to boost the tree cover in exactly these regions with high fire occurrence are an adaptation of trees to fire by increasing bark thickness in reponse to high fire frequencies or a stronger negative feedback between fire occurrence and fuel load. This stronger feedback should then reduce fire intensity and consequently fire mortality."

Page 15 -16 line 1: "although known variations in vegetation characteristics are not represented in models. . ." Provide a brief description of what is not represented? Bark thickness variability, size-structure? Consider adding a stronger concluding sentence to identify how these improvements will be helpful to models.

30) This is meant to refer to the differences found for instance by (Lehmann et al., 2014). These known differences are however not well enough understood to be implemented in models. We changed the sentence to: "Known variations in vegetation are not sufficiently understood to be represented in models. However, our finding that models do show differences in the fire-vegetation-climate relationships between continents shows that further exploration why models show differences can be helpful to better understand causes for intercontinental differences." We can only suggest improvements whether they will really be helpful or not needs to be tested with such modifications implemented in models and comparisons of simulations with and without these modifications.
We add as a last concluding sentence: "Overall the multivariate model evaluation highlights the potential for more targeted model improvements with respect to the interactions between climate, vegetation and fire, which are crucial for our understanding of future vegetation projections."

2 Reviewer 2

The ability of JSBACH to reproduce the observed relationship between fire, tree and grass cover and mean annual precipitation (MAP) was assessed using two different coupled fire models, with the implicit aim of guiding future model development. Analysis was split between continents to assess different regional climate-vegetation- fire relationships, and using present day and pre-industrial land use to assess the models ability to reproduce human impact on burnt area within bioclimate. The authors successfully demonstrates the potential of this approach by identifying too high tree cover at low precipitations, high burnt area in areas of low tree cover and cropland representation as key model weaknesses, before speculating on likely causes and solutions. The approach is relatively simple but, as the authors point out, is also quite a novel way of identifying areas for improvements in vegetation-fire models which will hopefully be adopted by other modelling groups. I also like that the paper is solely dedicated to model assessment, despite the distraction of including JSBACH-standard (see comments below), and I look forward to seeing if this results in better informed, targeted model improvements in the future. If so, it could be a process the rest of us in the fire modelling community could learn from.

I do, however have a serious concern about the choice of driving data that needs to be addressed before I recommend publication. I also have a few other major comments, although some might just require brief clarification through author response and small changes to the m/s. Given the potential changes to the manuscript required to address the first major comment, I have only included a few key specific suggestion for now, largely for the introduction.

JSBACH-fire was driven using simulated climate from the MIP Earth System Model. However, almost all the evaluation is of JSBACH-fire component alone. This is clearly a problem for the basic spatial evaluation in most section 3.1 and figure 1, where it is often unclear if mismatches in vegetation cover or burnt area is because of JSBACH itself or because of biases in the Earth System Models (ESM) climate simulation. As the rest of the paper is evaluating JSBACH in climate space, it could be argued that the choice of driving data doesn't matter. However, simulated climate biases could still be playing a role even here. For example, the authors only use MAP as a climate proxy. Inherent in MAPs influance on fire are the extreme conditions, specially the length dry periods, that increases susceptibility to burning. This is part of the reason for the wide range in fire and tree cover at a given MAP in all but the driest and wettest climates, and is invoked by the authors to explain different tree-MAP relationships in Australia.

31) We agree that biases in the forcing can have an influence on the model evaluation and that the same simulation driven with reanalysis data would have different results. While the traditional variable by variable evaluation for instance shown in figure 1 is highly dependend on spatial biases our approach presented here largely overcomes this limitation. The focus of this paper is on the multivariate comparison that evaluates the model in climate space. We use the standard JSBACH setup, which is the combination of JSBACH with MPI-ESM meteorology. As the fire is sensitive to a number of variables, evaluation of the model in a different setup wouldn't help to guide model development for a model that is almost only run in the coupled setup. The evaluation of the model within the climate space helps to reduce the impact of climate model biases on the model evaluation and therefore to focus on biases in the land surface model. Moreover, our motivation here is to evaluate the land surface model, a detailed evaluation of climate biases in the ECHAM model is therefore out of scope. Understanding potential influences of certain climate biases (such as extremes) on the simulation would require specific factorial experiments. While this would certainly increase our knowledge, it would not lead to an improvement of the coupled model system unless the climate biases can be improved. Mean annual precipitation explains a large part of the tree cover variability and therefore is a useful proxy for climate. Moreover we can relate model-data mismatches to this simple proxy, it is therefore informative. While certainly more parameters influence tree cover distribution an increasing number of variables included to explain patterns would require a totally different appraoch, as ours is largely based on the possibility to visualize the relationship between the variables. Three variables are a natural limit here (x-y scatter plot + color scale). We introduce our motivation for showing the geographic patterns and for our evaluation approach now in the beginning of the results section: "We first give an overview over the geographical distribution of the used observation and model output datasets. The comparison of geographical patterns is an important assessment of model performance, it is however difficult to assess whether the interactions between precipitation, fire and tree cover are well captured. Moreover as the JSBACH model is usually used as a land surface model for the MPI-ESM and therefore also here forced with MPI-ESM output, biases in model forcing can cause geographical biases of vegetation and fire variables even with a perfect fire and vegetation model. To reduce the influence of biases in forcing data

on the model-data comparison and allow to more closely evaluate the interactions between model components we propose a multivariate evaluation of climate-fire-vegetation relationships. We assess the robustness of observed relationships for two tree cover datasets and two spatial resolutions and compare them to the model simulations. The last paragraph of this section adresses the influence of land use change on the simulated relationships."

2.1 Choice of JSBACH driving data

JSBACH-fire was driven using simulated climate from the MIP Earth System Model. However, almost all the evaluation is of JSBACH-fire component alone. This is clearly a problem for the basic spatial evaluation in most section 3.1 and figure 1, where it is often unclear if mismatches in vegetation cover or burnt area is because of JSBACH itself or because of biases in the Earth System Models (ESM) climate simulation. As the rest of the paper is evaluating JSBACH in climate space, it could be argued that the choice of driving data doesn't matter. However, simulated climate biases could still be playing a role even here. For example, the authors only use MAP as a climate proxy. Inherent in MAPs influance on fire are the extreme conditions, specially the length dry periods, that increases susceptibility to burning. This is part of the reason for the wide range in fire and tree cover at a given MAP in all but the driest and wettest climates, and is invoked by the authors to explain different tree-MAP relationships in Australia. General Circulation Models (GCMs) are notoriously poor at simulating dry periods, with many underestimating the length and/or severity of dry periods due to poor simulation of convective vs persistent rainfall and a problem with persistent dizzle (DeAngelis et al. 2013; Gutowski et al. 2003). Length of dry periods is fundamental in the calculation of ignition probability and each fire's area in SPITFIREs rate of spread model (Thonicke et al. 2010). The "standard" fire model used in this study sounds like it could be similar to GLOBFIRM? If so, this is also very sensitive to number of dry days, with a rapid increase in burnt area in longer dry seasons (Thonicke et al. 2001), which would explain at least part the underestimation of maximum burnt areas. Either way, driving and comparing JSBACH with ESM output could skew the MAP relationships with fire and potentially tree cover in figure 3-6 and A1-2. This is by no means the only problem with driving the model with ESM data, but it is the one that springs to mind. Using MPI also required the authors to make a rather awkward decision between performing comparisons on different time periods (1996-2005 from JSBASH runs; 2001-2010 from observations) or on the few years of model-observation overlap.

I have two suggestion for how the authors could address this problem:

1. Continue to use the MPI driven runs, but reframe the paper to evaluate the processes and identify weaknesses in simulation of tree cover and fire in the ESM as a whole. Some of the arguments I have made above as to how ESMs simulated climate could affect tree cover and fire could be included. However, there are likely many more, some specific to MPI. If there are any special required configuration of JSBACH to simulate vegetation dynamics under MPI then these should also be included. The authors briefly touch on two arguments that could also be expanded: lines 11-14 on page 6 uses figure 1c to briefly discuss whether MPIs MAP biases as a reason for some of the mismatches between observed and simulated burnt area; and lines 7-15 on page 13 where the mismatches between driving data introduced straight into the fire model (popdensity, lightning etc) and those driven from MPI climate output. Section 3.1 should just need re-formulating with no new analysis. Subsequent sections may require fresh analysis, potentially looking at multivariate relationships within the space of MPIs driving data.

2. Run JSBACH with climate observations, including using common precipitation observations for driving data, and analysis of observed and simulated fire, MAP and vegetation cover. According to (Rabin et al. 2017), JSBACH model output should be included in fireMIP, in which case, vegetation cover by PFT and burnt area from observation driven JSBACH will be available from fireMIP.

32) See our previous reply. We include some of the points mentioned by the reviewer to improve the discussion on our setup choice (see below). Evaluating the details of climate biases of the MPI-ESM is out of scope of this manuscript. Clearly there can be biases due to climate biases in the simulations of JSBACH. However evaluating the model in a different setup seems less promising and less targeted to us than our approach to evaluate the model in climate space using the setup it is usually used with. As the reviewer also acknowledges we mention the limitation of the input datasets determining the ignitions as inconsistency. However regarding the conclusions we draw from our comparison we don't see a strong point that they would

be strongly affected. The reviewer states that the rainfall seasonality is especially important for the "wide range in fire and tree cover at a given MAP in all but the driest and wettest climates". We show that the relation between precipitation and burned area is captured quite nicely at least whith SPITFIRE and for the relation between MAP and tree cover we look at exactly the thresholds of these driest and wettest climates, not at the variability inbetween. For the intermediate rainfall regions we focus on the relationship between tree cover and fire. We don't see a good reason why other climate biases should decrease the correlation between fire and tree cover, which is the point of our focus here.
FireMIP simulations in this setup are unfortunately not available. Within the first round of FireMIP simulations (Rabin et al. 2017) the model was set up with prescribed vegetation. For recent simulations we did also similar simulations with dynamic vegetation however this model includes a number of changes, such that the versions are not comparable anymore. We include a paragraph on the model biases in the discussion of model improvements:
"Many climate models have problems to represent extremes, length of dry periods and tend to generate a permanent drizzle (DeAngelis et al., 2013; Gutowski et al., 2003). With our approach we only include mean annual precipitation, other aspects of the modelled climate are neglected but might contribute to model-data mismatches in the relationship between precipitation and other variables. Mean annual precipitation is however a strong driver of vegetation patterns especially in the tropics and including more climate parameters would require an entirely different approach and possibly limit visualization and interpretation of the results. Including more climatic parameters could especially help to interpret more of the variability for mean annual precipitation amounts that allow tree establishment but do not lead to complete canopy closure. The reasonable relationship of mean annual precipitation and burned area however indicates either that additional climate biases are not important as fire is quite sensitive to the length of dry seasons or that that the fire model cancels out additional climate biases."

2.2 Choice of fire dataset

Is there a reason for use of GFED4 instead of GFED4 with small fires (GFED4s) (van der Werf et al. 2017)? There may be a good reason for not including small fires, but given the prevalence of GFED4s in other fire evaluation studies (Rabin et al. 2017; Kelley et al. 2014; Kloster & Lasslop 2017), it might be worth including some justifi- cation. Also, are the certain weaknesses in fire detection in GFED that might affect the results? The missing smalls fire's for example should be mentioned as a caveat in relation to results from figure 3.

33) We use here the global burnt area dataset with the highest accuracy (Padilla et al., 2015). The dataset does underestimate small fires, and a recent version of GFED4 (GFED4s) tries to take these into account. However, the small fire detection procedure has been strongly criticized and is highly uncertain see eg, (interactive discussion van der Werf et al. (2017)). Therefore, we decide to use GFED4 for the moment as it has a proven high quality and refrain from using GFED4s until its accuracy has been shown. The spatial patterns of the two datasets are very similar (see Randerson et al., 2012, Figure 7), the main difference is that the GFED4s has a 25% higher burned area. These small fires are often related to croplands or deforestation. The models used here do not model deforestation or cropland fires, therefore aiming at this high burned area that includes these fires would not be an advantage. As far as we know there is no quantification of other weaknesses of the burned area datasets, therefore speculating about the extent and whether they would influence our results would be difficult. We add a reference to an evalutation study and mention the main sources of uncertainties. We add in the discussion section:
"The latest release of the GFED burned area and emissions datasets includes an extension for small fires (Randerson et al., 2012). However these small fires are often related to cropland fires or deforestation fires. Neither of these fire types are modelled explicitely in our model approaches and therefore could cause an unwanted mismatch. Cropland fires are not expected to strongly influence the vegetation cover, while deforestation is prescribed as described in the model and simulation paragraphs and therefore the influence on vegetation cover is considered. Burned area datasets are generally uncertain mainly due to the limited spatial and temporal resolution (Padilla et al., 2015), the difference in global burned area between the dataset including small fires and the one not including small fires is 25%. The spatial patterns are less affected, but missed burned areas due to high cloud cover certainly introduces also spatial biases. How important such errors are for a comparison as present here is unknown."

2.3 Quantification of similarity in multivariate relationships.

The observed relationship between MAP and tree cover is described as either "linear" for Australia and "sigmoid" for other continents, with the ability of each model to de- scribe each curve used as evidence when identifying model weakness. However, I'm not sure I can see these relationships. Observed Australia looks more like the start of a sigmoid (albeit with a shallower gradient when compared to e.g. Africa), "chopped" at low tree covers. South Africa looks more linear. A simple curve fitting and correlation could help determine how closely each continent resembles each function, and if the model is reproducing this relationship, which would place subsequent discussion on firmer ground.

34) This is an interesting idea and indeed the purely visual comparison was indeed not that firm. As likely only the maximum tree cover for a certain precipitation amount is limited by precipitation and lower tree covers are likely modified by other factors we used a quantile regression to characterize the relationship between precpitation and maximum tree cover. We use a linear regression and a local regression to illustrate the difference between the linear and nonlinear/sigmoid increase. We include a paragraph in the methods section:
We use quantile regressions to characterize the relationship between precipitation and maximum tree cover. The quantile regressions were computed with the R package quantreg (Koenker, 2018). We use the local quantile regression to characterize the shape of the increase in maxmimum tree cover for increasing precipitation. Moreover we quantify the deviation from a linear increase by also including the linear qunantile regression. Both regressions were computed for the 0.9 quantile. For the local quantile regression the bandwidth parameter was set to 300 and the number of points where the function was estimated was set to 10.
Adopted the paragraph in the results section:
"Models and observations show differences between continents in the relationship between precipitation and maximum tree cover (Figure 5). For Africa, South America and Asia the relationship between maximum tree cover and precipiation shows a saturation for high precipitation. For Australia maximum tree cover increases linearly with increasing precipitation for models and observations, but the precipitation range also does not reach values where a clear saturation is reached for the other continents. For JSBACH-standard the curves are very similar for the different continents. JSBACH-SPITFIRE shows a stronger variation, this must be due to the differences in fire as the model is otherwise the same. The observations show an even stronger variation between continent, with clearly lower tree cover valuse for Australia followed by Asia. For Africa local quantile regression clearly differs from the linear quantile regression for the satellite data, indicating a sigmoid shape, while the other continents show a rather linear increase until the saturation (Figure 5). JSBACH-SPITFIRE reproduces the higher tree cover for South America compared to Africa for mean annual precipitation lower than 1000 mm, but also JSBACH-standard shows a small difference."
In the discussion we remove the paragraph on the disucssion of the linear increase for Australia in comparison to the Lehmann et al. (2014) and focus on the point that models do also show some differences between the continents. We add in the end of the discussion:
The comparison of the increase in maximum tree cover with increasing precipiation shows that the model shows some variability in climate-vegetation-fire relationships between continents, it misses a large part of the variability. Finding the correct balance of the many influencing factors, e.g. climate, fire, land use, evolutionary differences, will remain a challenge for the future.

The remaining multivariate comparisons is also largely based on visual comparisons on plots. While this is an important part of assessing differences in simulated vs observed relationships, I feel like the comparison could do with some quantification using some simple multivariate metric, expanding on the two-variable assessment in Table 1. I am by no means an expert in multivariate statistics though, and perhaps a "simple" comparison isn't possible. But if the authors have any thoughts on this, it would be good to hear (and perhaps include them in the m/s?)

35) This is a very interesting suggestion. However we believe that such a metric would still need to be developed. We did not find an applicable, promising approach in a web search. Also we are not sure what this multivariate metric could represent. Correlations can only capture linear, rank correlations monotonic relationships. This made sense for precipitation and tree

cover, the relationship with fire however is more complex. Probably an approach based on regression methods, including also nonlinearities could be a way forward. This seems promising to us, however it would deserve more attention and in depth testing. Nevertheless we now also include the rank correlation between fire and tree cover for a certain precipitation and tree cover range in the Table 1 in addition to the correlation between precipiation and tree cover. This quantifies the stronger impact of SPITFIRE on tree cover compared to the observations and also reveals that JSBACH-standard has a reversed relationship between fire and tree cover, likely due to the exclusion of pastures for burning.

2.4 Use of two models

More could be made of the use of the "standard model" (JASBACH-standard) to help analyse MPI, JSBACH or even SPITFIRE performance, which is obviously the model the authors will use in future studies. As a start, JSBACH-standard could do with a little bit more description to help inform later discussion. Are the curves describing relation- ship between relative humidity, fuel carbon and fire similar to GLOBFIRM (Thonicke et al. 2001), or are they more similar to those simpler rate of spread models such as CTEM (Arora & Boer 2005). Are parameters used by the model based on literature, site comparisons, or optimization of remote sensing? If the latter, is its poor perfor- mance likely due to biases in JSBACH simulation of vegetation or MPI climate and dizzle biases? If the former, is it additionally due to fire model structure or bad pa- rameterizations? How much is PFT fraction remove after fire? Is 100% of burnt PFT removed, or just a fraction? If a fraction, does this vary? And does it vary by life form, PFT, burnt areas or some other relationship?

36) The simple fire parameterization is described as: "The JSBACH-standard fire computes burned area based on a minimum burned fraction which increases as a function of the litter carbon pools and relative humidity averaged over the last three weeks." And there is really not more in terms of burned area. So probably it is closer to GLOBFIRM, but it is also unclear how to quantify whether it is close to one or the other model. We add that the model was tuned to yield reasonable global emissions estimates and improve the tree cover, there was no comparison with site level or remote sensing products. We already included that:
"In the JSBACH-standard fire scheme the burned area directly translates into a reduction of the cover fractions of the plant functional types (PFTs) ..."
we add: "(100% of the cover fractions on burned area are removed)"

A better comparison between the two models in the discussion and/or conclusion might also further strength the case for use of multivariate approach. Despite its poor per- formance is there any part of the standard model multivariate relationship that could be used to guide development of SPITFIRE, particularly with respect PFT tree mor- tality? Is there any conclusion that can be drawn on the use of complex fire models to represent complex processes such as fire and fire-feedbacks, or does any part of the standard models performance (i.e, locations of fire occurrence) suggest that emer- gent behaviour of fire on coarse scales does not require the use of complex models? Does a comparison of strength and weakness of the two models say anything about the coupling to JSBACH or required configuration for use of JSBACH-fire in MPI?
Ofcourse, if the authors feel like nothing substantial can be learnt from comparing the two models, then they could consider removing JSBACH-standard from the m/s. However, there is nothing technically wrong with its inclusion, so I'll leave that for the authors to decide.

37) The comparison with the simple (poor permorming) fire model mainly shows that improvements in the fire model lead only to small improvements in vegetation patterns. We think that answers to the very specific questions of the reviewer would be highly speculative and would require additional analysis. It is also often unclear how much difference in performance is due to better tuning and how much due to a better model structure, as none of the models is optimized.

2.5 Specific comments

Page 2, line 24-25: The development of complex fire models actually started before widespread use of remotely sensed products. MC2 (Lenihan et al. 1998) forms the basis for most rate of spread models (Hantson et al. 2016), and SPITFIRE is itself a development of Reg-FIRM (Venevsky et al. 2002). Neither invoke the use of remote sensed burnt area.

38) We modify the sentence, the recent implementations of SPITFIRE for instance have made strong use of satellite data: "The development of remotely sensed global burned area products facilitated the implementation and evaluation of complex fire models within DGVMs (Hantson et al., 2016). "

Page 2, line 30: "the importance of benchmarking effects on vegetation has been noted" . Not just noted, but also done (Kelley et al. 2014).

39) We extended the sentence in the revised manuscript with:
... and applied in model development studies (Kelley and Harrison, 2014; Lasslop et al., 2014)

Page 3, line 11: Please use -180 to 180 coordinates longitudes.

40) We updated the coordinates for the South America region.

Page 4, line 2-3: Replace (or include along side) "(Rabin et al. 2017)" with "(Thonicke et al. 2010; Lasslop et al. 2014)" . (Rabin et al. 2017) does provide description of SPITFIRE alongside several other fire models, but the authors should also give credit to the model developers.

41) We refer to the two older publications in the beginning of the paragraph, where SPITFIRE is mentioned the first time. (Thonicke et al. 2010 is included there now too.) Rabin et al. provides the most up-to-date, complete and detailed description and therefore deserves a reference too.

Page 4, line 14: "During the 1000 year spin up period . . . " How was the spin-up determined? Where carbon or PFT fractions/burnt area in equilibrium by this point? How was this tested?

42) The spin-up period was determined based on experience, we did not apply a formal test criterium. PFTs are largely in equilibrium after 1000 years, small changes especially between woody PFTs can still take place in some grid cells. Global tree cover on the other hand equilibrates after around 300 years. We included:
"At the end of the 1000 years PFT distribution was largely in equilibrium with only minor shifts between woody PFTs in few grid cells."

Page 5, line 31 - Page 4 line 1: Please add a citation to the r-package paper. I think (Tuck et al. 2014) is the correct reference, but the authors should check. Also include a direct reference to the r package used. Typing in the following in an R terminal should give you the require bibtex information:
» citation(«package name»)

43) We included the publication indicated with the citation command (Mattiuzzi and Detsch, 2018). Tuck et al. 2014 seems to be the citation for the MODISTools package.

Page 5, lines 12-13: Is any scaling applied when translating from LIS/OTD flash count to ignition sources? I.e, are cloud-cloud flashs removed?

44) Cloud-cloud flashes are removed, however, we refer to the model description papers for the exact model formulations and here only document the input files. We also don't detail how population density is converted into ignitions and want to keep a similar level of details for the lightning ignitions.

Page 11, line 10 - Page 12, line 1: (Kelley et al. 2014) collected cite based bark thick- ness data to reparametrize bark thickness in a SPITFIRE based model. There might also be some Australia specific improvements in this paper that could be considered.

45) Yes, we include the reference to Kelley et al. 2014 for the bark thickness as an adaptive trait and the resprouting mechanism which acts in a similar way to increase tree cover:
"Kelley and Harrison (2014) included bark thickness as an adaptive trait in the LPX model, which increased and improved the tree cover for Australia. Resprouting is another important mechanism that leads to an increase in tree cover in fire affected areas (Kelley and Harrison, 2014)." see also reply 10.

Page 14, lines 21 - 23: The non-independence of vegetation cover datasets should be included when introducing the datasets on page 4 and 5.

46) We mention the similarity of the two datasets in the methods section in the revised manuscript.
"The datasets rely on different sensors, however, the algorithms to derive vegetation cover are very similar and the datasets therefore not completely independent. Nevertheless using the two datasets can give a first insight on the robustness of the investigated patterns."

Page 17: Please complete author contributions.

47) We completed the author contributions.

References

Avitabile, V., Herold, M., Heuvelink, G. B. M., Lewis, S. L., Phillips, O. L., Asner, G. P., Armston, J., Ashton, P. S., Banin, L., Bayol, N., Berry, N. J., Boeckx, P., de Jong, B. H. J., DeVries, B., Girardin, C. A. J., Kearsley, E., Lindsell, J. A., Lopez-Gonzalez, G., Lucas, R., Malhi, Y., Morel, A., Mitchard, E. T. A., Nagy, L., Qie, L., Quinones, M. J., Ryan, C. M., Ferry, S. J. W., Sunderland, T., Laurin, G. V., Gatti, R. C., Valentini, R., Verbeeck, H., Wijaya, A., and Willcock, S.: An integrated pan-tropical biomass map using multiple reference datasets, Glob. Chang. Biol., 22, 1406–1420, https://doi.org/10.1111/gcb.13139, http://doi.wiley.com/10.1111/gcb.13139, 2016.

Baccini, A., Goetz, S. J., Walker, W. S., Laporte, N. T., Sun, M., Sulla-Menashe, D., Hackler, J., Beck, P. S. A., Dubayah, R., Friedl, M. A., Samanta, S., and Houghton, R. A.: Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps, Nat. Clim. Chang., 2, 182–185, https://doi.org/10.1038/nclimate1354, http://www.nature.com/articles/nclimate1354, 2012.

DeAngelis, A. M., Broccoli, A. J., and Decker, S. G.: A Comparison of CMIP3 Simulations of Precipitation over North America with Observations: Daily Statistics and Circulation Features Accompanying Extreme Events, J. Clim., 26, 3209–3230, https://doi.org/10.1175/JCLI-D-12-00374.1, http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-12-00374.1, 2013.

Gutowski, W. J., Decker, S. G., Donavon, R. A., Pan, Z., Arritt, R. W., and Takle, E. S.: Temporal–Spatial Scales of Observed and Simulated Precipitation in Central U.S. Climate, J. Clim., 16, 3841–3847, https://doi.org/10.1175/1520-0442(2003)016<3841:TSOOAS>2.0.CO;2, http://journals.ametsoc.org/doi/abs/10.1175/1520-0442{%}282003{%}29016{%}3C3841{%}3ATSOOAS{%}3E2.0.CO{%}3B2, 2003.

Hantson, S., Arneth, A., Harrison, S. P., Kelley, D. I., Prentice, I. C., Rabin, S. S., Archibald, S., Mouillot, F., Arnold, S. R., Artaxo, P., Bachelet, D., Ciais, P., Forrest, M., Friedlingstein, P., Hickler, T., Kaplan, J. O., Kloster, S., Knorr, W., Lasslop, G., Li, F., Mangeon, S., Melton, J. R., Meyn, A., Sitch, S., Spessa, A., van der Werf, G. R., Voulgarakis, A., and Yue, C.: The status and challenge of global fire modelling, Biogeosciences Discuss., pp. 1–30, https://doi.org/10.5194/bg-2016-17, http://www.biogeosciences-discuss.net/bg-2016-17/, 2016.

Hantson, S., Scheffer, M., Pueyo, S., Xu, C., Lasslop, G., van Nes, E. H., Holmgren, M., and Mendelsohn, J.: Rare, Intense, Big fires dominate the global tropics under drier conditions, Sci. Rep., 7, 14 374, https://doi.org/10.1038/s41598-017-14654-9, http://www.nature.com/articles/s41598-017-14654-9, 2017.

Hoffmann, W. a., Orthen, B., and Vargas Do Nascimento, P. K.: Comparative fire ecology of tropical savanna and forest trees, Funct. Ecol., 17, 720–726, https://doi.org/10.1111/j.1365-2435.2003.00796.x, 2003.

Hoffmann, W. a., Geiger, E. L., Gotsch, S. G., Rossatto, D. R., Silva, L. C. R., 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, 759–68, https://doi.org/10.1111/j.1461-0248.2012.01789.x, http://www.ncbi.nlm.nih.gov/pubmed/22554474, 2012.

Kelley, D. I. and Harrison, S. P.: Enhanced Australian carbon sink despite increased wildfire during the 21st century, Environ. Res. Lett., 9, 104 015, https://doi.org/10.1088/1748-9326/9/10/104015, http://stacks.iop.org/1748-9326/9/i=10/a=104015?key=crossref.d09b4fd55bf91ab5f53656426beba387, 2014.

Koenker, R.: quantreg: Quantile Regression, https://cran.r-project.org/package=quantreg, 2018.

Lasslop, G., Thonicke, K., and Kloster, S.: SPITFIRE within the MPI Earth system model: Model development and evaluation, J. Adv. Model. Earth Syst., 6, 740–755, https://doi.org/10.1002/2013MS000284, http://doi.wiley.com/10.1002/2013MS000284, 2014.

Lehmann, C. E. R., Anderson, T. M., Sankaran, M., Higgins, S. I., Archibald, S., Hoffmann, W. A., Hanan, N. P., Williams, R. J., Fensham, R. J., Felfili, J., Hutley, L. B., Ratnam, J., San Jose, J., Montes, R., Franklin, D., Russell-Smith, J., Ryan, C. M., Durigan, G., Hiernaux, P., Haidar, R., Bowman, D. M. J. S., and Bond, W. J.: Savanna Vegetation-Fire-Climate Relationships Differ Among Continents, Science (80-.)., 343, 548–552, https://doi.org/10.1126/science.1247355, http://www.sciencemag.org/cgi/doi/10.1126/science.1247355, 2014.

Mattiuzzi, M. and Detsch, F.: MODIS: Acquisition and Processing of MODIS Products, https://cran.r-project.org/package=MODIS, 2018.

Padilla, M., Stehman, S. V., Ramo, R., Corti, D., Hantson, S., Oliva, P., Alonso-Canas, I., Bradley, A. V., Tansey, K., Mota, B., Pereira, J. M., and Chuvieco, E.: Comparing the accuracies of remote sensing global burned area products using stratified random sampling and estimation, Remote Sens. Environ., https://doi.org/10.1016/j.rse.2015.01.005, http://linkinghub.elsevier.com/retrieve/pii/S0034425715000140, 2015.

Pellegrini, A. F. A., Anderegg, W. R. L., Paine, C. E. T., Hoffmann, W. A., Kartzinel, T., Rabin, S. S., Sheil, D., Franco, A. C., and Pacala, S. W.: Convergence of bark investment according to fire and climate structures ecosystem vulnerability to future change, Ecol. Lett., 20, 307–316, https://doi.org/10.1111/ele.12725, http://doi.wiley.com/10.1111/ele.12725, 2017.

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. Geophys. Res. Biogeosciences, 117, G04 012, https://doi.org/10.1029/2012JG002128, http://doi.wiley.com/10.1029/2012JG002128, 2012.

Saatchi, S. S., Harris, N. L., Brown, S., Lefsky, M., Mitchard, E. T. A., Salas, W., Zutta, B. R., Buermann, W., Lewis, S. L., Hagen, S., Petrova, S., White, L., Silman, M., and Morel, A.: Benchmark map of forest carbon stocks in tropical regions across three continents., Proc.

Natl. Acad. Sci. U. S. A., 108, 9899–904, https://doi.org/10.1073/pnas.1019576108, http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3116381{&}tool=pmcentrez{&}rendertype=abstract, 2011.

van der Werf, G. R., Randerson, J. T., Giglio, L., van Leeuwen, T. T., Chen, Y., Rogers, B. M., Mu, M., van Marle, M. J. E., Morton, D. C., Collatz, G. J., Yokelson, R. J., and Kasibhatla, P. S.: Global fire emissions estimates during 1997–2016, Earth Syst. Sci. Data, 9, 697–720, https://doi.org/10.5194/essd-9-697-2017, http://www.earth-syst-sci-data-discuss.net/essd-2016-62/https://www.earth-syst-sci-data.net/9/697/2017/, 2017.

Tropical climate-vegetation-fire relationships: multivariate evaluation of the land surface model JSBACH

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Abstract. The interactions between climate, vegetation and fire can strongly influence the future trajectories of vegetation in Earth system models. We evaluate the relationships between tropical climate, vegetation and fire in the global vegetation model JSBACH, using a simple fire scheme and the complex fire model SPITFIRE with the aim to identify potential for model improvement. We use two remote sensing products (based on MODIS and Landsat) in different resolutions to assess the robustness of the obtained observed relationships. We evaluate the model using a multivariate comparison that allows to focus on the interactions between climate, vegetation and fire and test the influence of land use change on the modelled patterns. Climate-vegetation-fire relationships are known to differ between continents we therefore perform the analysis for each continent separately.

The observed relationships are similar in the two satellite datasets, but maximum tree cover is reached at higher precipitation values for coarser resolution. The model captures the broad spatial patterns with regional differences, which are partly due to the climate forcing derived from an Earth system model. SPITFIRE strongly improves the spatial pattern of burned area and the distribution of burned area along increasing precipitation compared to the simple fire scheme. Surprisingly the correlation between precipitation and tree cover is higher in the observations than in the largely climate driven vegetation model, with both fire models. The multivariate comparison identifies ~~a too high~~ an excessive tree cover in low precipitation areas and a too strong relationship between high fire occurrence and low tree cover for the complex fire model. We therefore suggest that drought effects on tree cover and the impact of burned area on tree cover or the adaptation of trees to fire can be improved. ~~The model reproduces the linear increase of tree cover with increasing precipitation for Australia, compared to the sigmoid increase for the other continents. As we find this linear increase for both fire models as well as for present day and preindustrial land use, we conclude that it appears in the model due to differences in climate not captured by mean annual precipitation~~ The observed variation of the relationship between precipitation and maximum tree cover is higher than the modelled variation. Land use contributes to the intercontinental differences in fire regimes with SPITFIRE and strongly overprints the modelled multimodality of tree cover with SPITFIRE.~~The multivariate comparison between observations and model~~

The multivariate model-data comparison used here has several advantages: it improves the attribution of model-data mis-

matches to model processes, it reduces the impact of biases in the meteorological forcing on the evaluation and it allows to evaluate not only a specific target variable but also the interactions.

Copyright statement.

1 Introduction

Capturing the interactions of vegetation cover and composition with the climatic drivers and related disturbances in Earth system models is crucial to provide reliable changes of vegetation for a changing climate. Climate is the main driver of global vegetation patterns, but also vegetation has crucial impacts on the Earth system, due to its influence on the surface albedo and the water cycle (Bonan, 2008; Brovkin et al., 2009). The importance of vegetation type has been assessed in various studies: when compared to grasslands, forests in tropical areas cool the climate due to higher evapotranspiration while in boreal regions, forests warm the climate due to a reduction of the albedo (Bathiany et al., 2010). The relevance of vegetation also shows when contrasting vegetated and non-vegetated surfaces: in the Sahel region this difference is of major importance for the climatic conditions (Brovkin et al., 1998).

Interactions between vegetation, fire and climate are particularly important to understand the spatial patterns in tropical vegetation, which is characterized by strong gradients from deserts to tropical rainforests. Remotely sensed tropical tree cover shows a bimodality between forest (T>60%) and savanna (T<60%) states for grid cells with similar climate. Intermediate tree cover fractions (e.g. 60%) are virtually absent (Hirota et al., 2011; Staver et al., 2011b). The occurrence of this "gap" in tree cover was suggested to be caused by a feedback between fire and vegetation. Although the reliability of remotely sensed tree cover sets to diagose this "gap" was recently questioned (Gerard et al., 2017), the bimodality in the distribution is also confirmed by canopy height (Xu et al., 2016) or biomass (Yin et al., 2014). The occurrence of both forest and savanna states under similar climate conditions due to a feedback between fire and vegetation is supported by conceptual (Staver et al., 2011a) and process-based models (Higgins and Scheiter, 2012; Moncrieff et al., 2014; Lasslop et al., 2016).

While data analysis can provide insights on driving factors for certain variables, process-based models summarize the process understanding and allow us to perform experiments that are impossible in reality. Dynamic global vegetation models (DGVMs) were developed to understand ecosystem dynamics, the carbon cycle and biosphere-atmosphere interactions (Sitch et al., 2003). Many of them are part of Earth system models (ESMs), to represent the dynamics of the land surface within the climate system. It is therefore important that DGVMs include appropriate representations of vegetation to obtain reliable simulations of the Earth system (e.g. Baudena et al., 2015).

The development of remotely sensed global burned area products ~~triggered the development~~ facilitated the implementation and evaluation of complex fire models within DGVMs (Hantson et al., 2016). Over the recent years these models were applied to address the impact of fire on the carbon cycle (Li et al., 2014; Yue et al., 2016), the land surface temperature (Li et al., 2017) or the sensitivity of the fire model to driving factors (Kloster et al., 2010; Lasslop and Kloster, 2015). Evaluation of fire models mostly

focused on evaluating the burned area and carbon emissions, but also the importance of benchmarking effects on vegetation has been noted (Hantson et al., 2016) and applied in model development studies (Kelley and Harrison, 2014; Lasslop et al., 2014). The evaluation, however, is based on comparing variables one by one and not the relationships between them. (Baudena et al., 2015) go beyond the geographic comparison by analyzing the relationship between tree cover and the main climatic driver (precipitation). Also the relationship between precipitation and climate was evaluated in previous studies (Prentice et al., 2011). However, to our knowledge, climate, vegetation and fire have not been combined in a multivariate model-observation comparison.

Here, we aim 1) to assess the robustness of observed climate-vegetation-fire relationships across the tropical continents based on two remotely sensed tree cover datasets; 2) to test a multivariate model evaluation to identify opportunities for model improvements in JSBACH, the vegetation model used within the MPI Earth system model, and 3) to test the contribution of land use change on the obtained relationships.

2 Model and Data

To investigate the climate-fire-vegetation relationships in the tropical regions we represent climate by the mean annual precipitation (P), vegetation by the tree (TC), grass (GC) and non-vegetated cover and fire as the burned fraction (BF).

We define the tropical region as between -30° and 30° latitude. As continental limits we chose -20 to 60 longitude and -30 to 30 latitude for Africa, ~~230~~-130 to ~~330~~-30 longitude and -30 to 30 latitude for South America, 60 to 160 longitude and -10 to 30 latitude for Asia and 100° to 160° longitude and -30 to -10 latitude for Australia.

2.1 Model and simulation description

We use the JSBACH land surface model (Reick et al., 2013), which is the land component of the MPI Earth system model (MPI-ESM) (Giorgetta et al., 2013). JSBACH simulates the terrestrial carbon and water cycle in a process based way. We use two fire algorithms, a simple empirical model (Brovkin et al., 2009; Reick et al., 2013) and the process-based fire model SPITFIRE ~~(Lasslop et al., 2014)~~(Lasslop et al., 2014; Thonicke et al., 2010). Results referring to simulations with the complex SPITFIRE model are referred to as JSBACH-SPITFIRE, simulations with the simple JSBACH standard fire scheme are indicated as JSBACH-standard. These two approaches span the range of complexity of currently used global scale fire models (Hantson et al., 2016). The JSBACH-standard fire computes burned area based on a minimum burned fraction which increases as a function of the litter carbon pools and relative humidity averaged over the last three weeks. It was tuned to yield reasonable global emission estimates (around 2PG) and to improve the tree cover, which is clearly too high without fire. SPITFIRE computes burned area based on human and lightning ignitions, fire spread rate and a fire duration. SPITFIRE distinguishes between different fuel particle sizes and uses a combination of minimum and maximum temperature, precipitation and soil moisture to determine the fuel moisture. Both fire models interact with the vegetation model as follows: JSBACH provides fuel amounts, vegetation composition and soil moisture as inputs to the fire model. The fire model in turn reduces the carbon pools of JSBACH according to the simulated carbon combustion of vegetation fires and reduces the cover fractions of burned

vegetation. In the JSBACH-standard fire scheme the burned area directly translates into a reduction of the cover fractions of the plant functional types (PFTs) ~~, while~~ (100% of the cover fractions on burned area are removed). Whereas in SPITFIRE the mortality of woody vegetation depends on the fire intensity, fire residence time, the vegetation height and bark thickness. The model's plant functional types for the tropics include C3 and C4 grass, tropical evergreen and deciduous trees, and rain green shrubs. Shrubs and trees compete according to their net primary productivity. Grasses and shrubs have an advantage compared to trees in regions with disturbances due to their lower establishment time scale (Reick et al., 2013, grasses: 1 year, shrubs: 12 years, tropical trees: 30 years). PFTs do not establish if the 5 years running mean net primary productivity (NPP) turns negative. Land use is included following the protocol of Hurtt et al. (2011). The implementation is described in detail in (Reick et al., 2013). Croplands are excluded from fire occurrence while pastures are treated as natural grasslands with a higher fuel bulk density within ~~SPITFIRE~~ JSBACH-SPITFIRE (Rabin et al., 2017). The JSBACH-standard fire excludes fire occurrence on both anthropogenic land cover types. JSBACH-SPITFIRE shows a reasonable agreement with remotely sensed data products for present day burned area and carbon emissions for simulations with prescribed land cover (Lasslop et al., 2014). The present setup with dynamic biogeography has been evaluated along the human dimensions population density and cropland fraction. The model tends to overestimate burned fraction for high cropland fractions and underestimates burned fraction for very low and high population densities (Lasslop and Kloster, 2017).

2.1.1 Simulation setup

JSBACH was forced with meteorological data extracted from a coupled simulation with the MPI-ESM version 1.1 for the historical period 1850-2005. The SPITFIRE model additionally uses a population density dataset (Klein Goldewijk et al., 2001) with decadal resolution and a monthly lightning climatology (LIS/OTD product of the LIS/OTD Science Team, http://ghrc.msfc.nasa.gov) as input for the computation of ignitions. The model's spatial resolution is 1.875° x 1.875°. The time step for plant productivity and hydrology is 30 minutes, while the disturbance routine is called once per day. During the 1000 year spinup period the first 28 years of forcing (1850-1877) were recycled and CO2 concentration fixed at the value of 1850 (284.725 ppm). At the end of the 1000 years PFT distribution was largely in equilibrium with only minor shifts between woody PFTs in few grid cells. The subsequent transient historical simulation (Hist) from 1850-2005 accounts for the changes in atmospheric CO2, climate, population density and land use. A complementary simulation accounting only for the rise in atmospheric CO2, transient climate and population density but using the land use of 1850 for the whole period (cLU) is used to isolate the effect of land use change on the climate - vegetation - fire relationships. When comparing the model output to observations, the averaging period for the model simulations was 1996-2005, as the forcing was only available until 2005.

2.2 Datasets for model evaluation

We averaged the remote sensing datasets over the years that were covered by all datasets (2001-2010). Model output is only available until the year 2005. Using only the overlapping period (2001-2005) would decrease the robustness of the mean fire regime and climate characterization. We therefore use different averaging periods for model (1996-2005) and observations (2001-2010). The presentation of the relationship between precipitation, tree cover and burned fraction based on remote sensing

data is based on 0.25 resolution and for the comparison with the model the datasets were aggregated to the model resolution (1.875x1.875).

2.2.1 Vegetation and land cover

We use two tree cover datasets based on satellite data, one based on the MODIS (moderate-resolution imaging spectroradiometer) sensor (Townsend et al., 2011), the other on the Landsat satellite (Hansen et al., 2013). Additionally we use the non-tree vegetation cover and non-vegetation cover of the MOD44B product version 051 (downloaded 6/February 2017, using the R modis package).(Mattiuzzi and Detsch, 2018)). The datasets rely on different sensors, however, the algorithms to derive vegetation cover are very similar and the datasets are therefore not completely independent. Nevertheless using the two datasets can give a first insight on the robustness of the investigated patterns.
The maximum tree cover in the MODIS dataset is 80%. This however corresponds to 100% crown cover (Hansen et al., 2003). The modelled cover fractions represent rather the crown cover with a 100% maximum, we therefore linearly rescaled the tree cover data to improve the consistency between model and observations. The second dataset based on Landsat data builds on a high spatial resolution of 30m (Hansen et al., 2013). The dataset provides annual forest gain and loss over the period from 2000-2012. Alkama and Cescatti (2016) reconstructed the annual tree cover and aggregated the dataset to 0.05° . Here, we used the mean over their reconstructed annual tree cover values from 2001-2010.
The MODIS collection 5 land cover dataset (Friedl et al., 2010) was used to test the influence of shrub lands (open and closed shrub lands), as the tree cover data have a higher uncertainty for shrublands. The filtering was applied on 0.05° spatial resolution. This dataset is distributed by the Land Processes Distributed Active Archive Center (LP DAAC), located at the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center (lpdaac.usgs.gov), distributed in netCDF format by the Integrated Climate Data Center (ICDC, http://icdc.cen.uni-hamburg.de) University of Hamburg, Hamburg, Germany in 0.05° spatial resolution and annual time step.

2.2.2 Fire

The global fire emissions database (GFED, http://www.globalfiredata.org/) provides globally gridded monthly burned area based on the MODIS sensor. We used the version 4 of the dataset (Giglio et al., 2013).

2.2.3 Precipitation

The "TRMM and Other Data Precipitation Data Set" (TMPA) is based on the Version 7 TRMM Multi-satellite Precipitation Analysis algorithm (Huffman et al., 2007, 2010). The product has near global coverage from 50° north to 50° south. The precipitation estimate (including rain, drizzle, snow, graupel and hail) is based on a combination of multiple data sources including precipitation gauges. The dataset is available online (http://disc.sci.gsfc.nasa.gov/gesNews/trmm_v7_multisat_precip).

2.3 Quantile regression

We use quantile regressions to characterize the relationship between precipitation and maximum tree cover. The quantile regressions were computed with the R package quantreg (Koenker, 2018). We use the local quantile regression to characterize the shape of the increase in maxmimum tree cover for increasing precipitation. Moreover we quantify the deviation from a linear increase by also including the linear qunantile regression. Both regressions were computed for the 0.9 quantile. For the local quantile regression the bandwidth parameter was set to 300 and the number of points where the function was estimated was set to 10.

3 Results

We first give an overview over the geographical distribution of the used observation and model output datasets. The comparison of geographical patterns is an important assessment of model performance, it is however difficult to assess whether the interactions between precipitation, fire and tree cover are well captured. Moreover as the JSBACH model is usually used as a land surface model for the MPI-ESM and therefore also here forced with MPI-ESM output, biases in model forcing can cause geographical biases of vegetation and fire variables even with a perfect fire and vegetation model. To reduce the influence of biases in forcing data on the model-data comparison and allow to more closely evaluate the interactions between model components we propose a multivariate evaluation of climate-fire-vegetation relationships. We assess the robustness of observed relationships for two tree cover datasets and two spatial resolutions and compare them to the model simulations. The last paragraph of this section adresses the influence of land use change on the simulated relationships.

3.1 Spatial distribution of vegetation cover, area burnt and precipitation in the tropics

The two observational satellite based tree cover datasets are consistent and show only small differences in their spatial pattern (Figure 1a). The overall clear pattern in tree cover is a transition from very high tree cover in moist rain forest regions to low tree cover in the drier savannas to the absence of trees in the desert regions. Both models reproduce this overall observed pattern, although with marked local differences. Both model versions overestimate tree cover in northern Australia to a similar extent. In the North-Eastern Amazon region the simulations underestimate tree cover compared to the observations. This underestimation is much smaller for JSBACH-SPITFIRE. The simulations overestimate tree cover in Southern Hemisphere Africa, this overestimation is again smaller for JSBACH-SPITFIRE. The simulated grass cover has higher maximum values, but generally is often lower than observed by satellite (Figure 1 d). The non-vegetated fraction is captured well by the models (Figure 1 e).

Generally JSBACH-standard strongly underestimates the total area burnt and the spatial variability (Figure 1 b). JSBACH-SPITFIRE improves the capability to represent fire regimes with high fire occurrences. The tropical average burned area per year is for JSBACH-standard 65 Mha, for JSBACH-SPITFIRE 242 Mha and for the satellite dataset 315 Mha. In South America spatial patterns in JSBACH-standard are inconsistent with the observations (most burning in the Northeast). JSBACH-SPITFIRE overestimates fire occurrence in South America but the spatial patterns are more similar to observations. In Africa we find reasonable agreement between JSBACH-SPITFIRE and the observations. JSBACH-standard shows a strong underes-

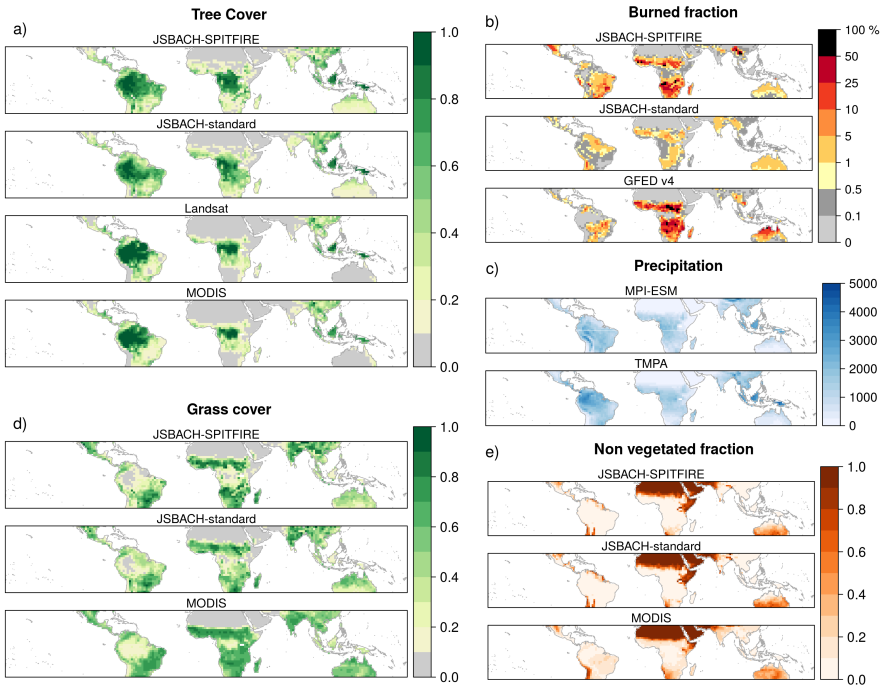

Figure 1. Spatial distribution of modelled and observed datasets used in this study. (a): Spatial distribution of tree cover fraction over the global tropics for the JSBACH-SPITFIRE and JSBACH-standard model simulation and the satellite data products from Landsat and MODIS. (b): Burned fraction [year^{-1}] as modeled by JSBACH-SPITFIRE and JSBACH-standard and the GFED v4 satellite product. (c): Precipitation in mm year^{-1} of the MPI-ESM and the TMPA dataset. (d): Grass cover fraction, and (e): non-vegetated fraction of the grid cell for the models and the MODIS satellite product. All datasets were remapped to the 1.875° model resolution.

timation of the burned fraction (max. 10% of the grid cell area year^{-1}, while the observations show up to 100%). In Australia JSBACH-SPITFIRE and JSBACH-standard show similar patterns and both strongly underestimate the burned ~~area~~fraction. Precipitation of the MPI-ESM forcing shows a dry bias in the East and central Amazon region, a dry bias in Asia, and moister conditions in the western part of southern hemisphere Africa (Figure 1 c). The dry bias in South America and Asia is known from previous ECHAM model versions (Hagemann et al., 2013; Stevens et al., 2013). The dry bias in precipiation in the Amazon may for instance explain the high bias in burned ~~area~~ fraction in that region.

3.2 Climate-fire-vegetation relationships: comparison of observation datasets

Maximum tree cover shows an increase along the precipitation gradient across all continents, with trees being absent until a certain threshold (300-500 mm year^{-1}), increasing maximum tree cover and saturation of maximum tree cover for high precipitation (between 1500 and 2000 mm year^{-1}). The two remotely sensed tree cover datasets are consistent in their variation

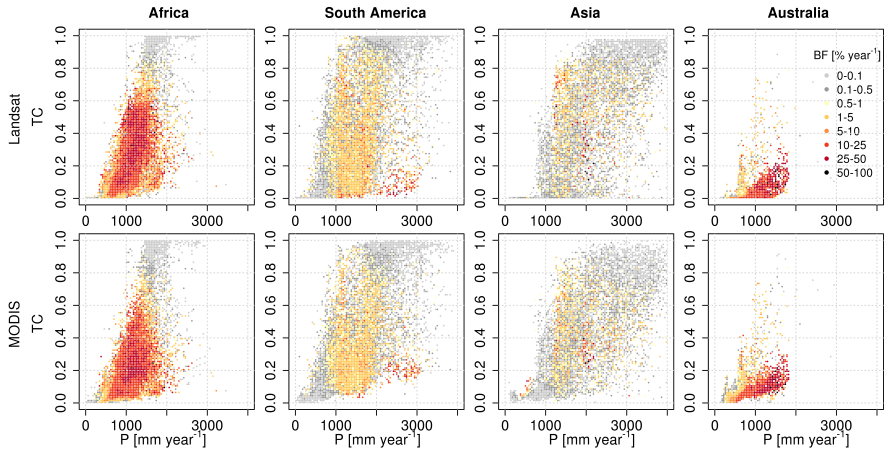

Figure 2. Tree cover (TC) versus precipitation [mm year^{-1}] with color coded burned fraction (BF) for different continents for the two satellite datasets. Burned area is averaged over data points with the same precipitation (40 mm steps) and tree cover (in steps of 0.01) to avoid over-plotting based on a spatial resolution of 0.25°. For Asia some higher precipitation values were cut off.

along the precipitation gradient (Figure 2). Fire occurrence is much higher for the African and Australian continent compared to South America and Asia. Burned fraction increases with increasing precipitation until around 1000mm mean annual precipitation, due to the increasing availability of fuels. For tree cover fractions higher than 0.8, fire is virtually absent. Beyond this distinction there is no visually clear increase in burned fraction for decreasing tree cover at a given precipitation value. The Spearman rank correlation between burned fraction and tree cover for grid cells with mean annual precipitation higher than 1000mm and tree cover lower than 0.8 is, however, significant for both datasets in the 0.25° resolution, in the model resolution only the correlation with the MODIS dataset is significant. This correlation is much stronger for the MODIS tree cover compare to the LANDSAT tree cover (Table 1). For Australia and Africa fire occurrence is very low below a mean annual precipitation of 300 mm year^{-1}, for South America and Asia already below 500 mm year^{-1}.

The Spearman rank correlation between precipitation and tree cover is very similar for both tree cover datasets (Table ~~1~~1). The statistical precipitation thresholds for low (but higher than 0) and high tree cover differ by less than 100 mm. The aggregation to the model resolution shows the strongest effect on the precipitation threshold for high tree cover and shifts this value to higher precipitation. The association between precipitation and burned area is less sensitive to the aggregation: 80% of the global burned area occurs in regions with precipitation between 609 and 1518 mm on 0.25° resolution and between 635 and 1495 mm in 1.875° resolution.

Table 1. Spearman rank correlation (R) between precipitation (P) and tree cover (TC), and rank correlation between burned fraction (BF) and TC for data points with mean annual precipitation higher than 1000mm and tree cover less than 0.8. The required precipitation [mm year^{-1}] for 0.05 < TC < 0.15 and 0.85 < TC < 0.95, estimated as 0.05 quantile of precipitation for grid cells with the specific TC only, and precipitation value [mm year^{-1}] where 10% and 90% of the burned area (BA) originates from areas with lower precipitation. For the remote sensing datasets TMPA was used as precipitation, for the simulations (Hist, cLU, and JSBACH-standard) the MPI-ESM precipitation was used. Model results are all in 1.875° resolution.

Data	R(P,TC)	R(BF,TC)	0.05 quantile of P for 0.05 < TC < 0.15	0.05 quantile of P for 0.85 < TC < 0.95	10% of BA has lower P	90% of BA has lower P
Landsat 0.25°	0.90	-0.05	568	1417		
Landsat 1.875°	0.91	-0.08	569	1596		
MODIS 0.25°	0.91	-0.26	425	1514		
MODIS 1.875°	0.93	-0.4	462	1644		
GFED v4 0.25°					607	1517
GFED v4 1.875°					635	1489
JSBACH-SPITFIRE Hist	0.79	-0.5	31	1268	652	1663
JSBACH-SPITFIRE cLU	0.78	-0.64	13	1000	700	1654
JSBACH-standard	0.87	0.17	34	1597	266	1519

3.3 Climate-fire-vegetation relationships: Evaluation of model results

In the tropics the observed burned area is strongly constrained by precipitation, around 80% of the burned area is observed in regions with mean annual precipitation between 600 and 1500 mm year^{-1} (Table 1). This precipitation range is slightly larger for the model simulations (Table 1). JSBACH-SPITFIRE reproduces the increase in burned area for low precipitation, but slightly overestimates the contribution of grid cells with precipitation higher than ca. 1300 mm year^{-1} to the total burned area (Figure 3). JSBACH-standard overestimates the contribution of areas with low precipitation, but agrees well on the contribution of areas with high precipitation (>1300 mm year^{-1}) when compared to the satellite observations. ~~Cumulative burned area normalized with the total burned area for increasing precipitation. For the GFEDv4 burned area the TMPA dataset was used, for the model simulations the MPI-ESM precipitation was used. Modelled and observed tree cover (TC) versus precipitation (P), color coded burned area fraction (BF). Satellite datasets were aggregated to model grid resolution (1.875°). Tree cover is overestimated for low precipitation values (< 500 mm year^{-1}) in simulations with both fire models (Figure 4).~~ Fire occurrence is limited in regions with low precipitation due to low fuel availability (Krawchuk and Moritz, 2011). This low fire occurrence

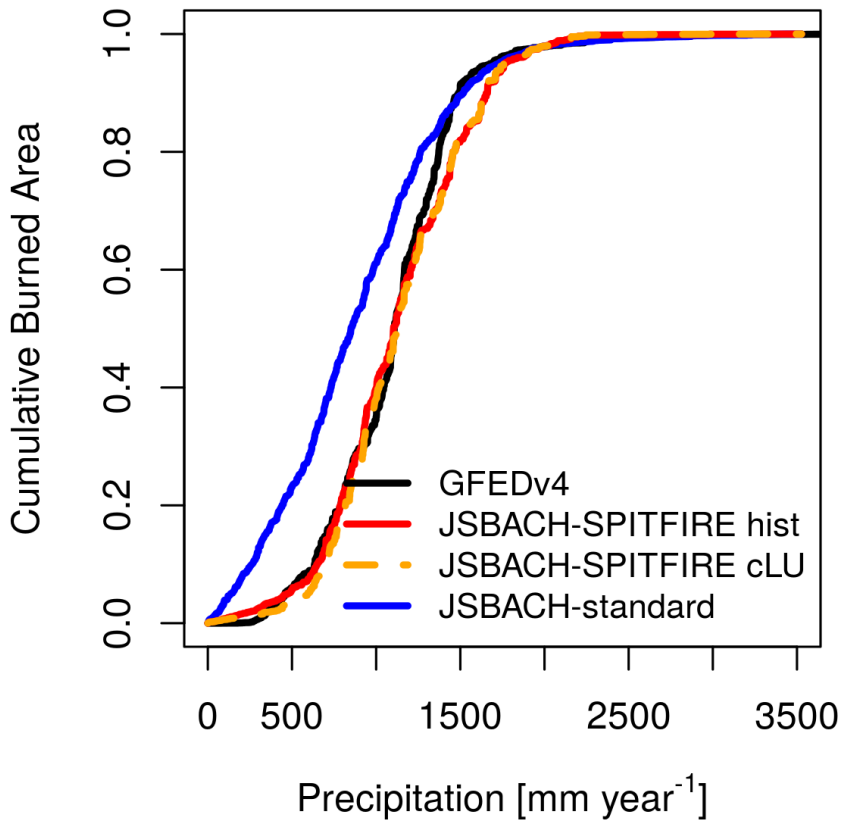

Figure 3. Cumulative burned area normalized with the total burned area for increasing precipitation. For the GFEDv4 burned area the TMPA dataset was used, for the model simulations the MPI-ESM precipitation was used.

is well reproduced by JSBACH-SPITFIRE and for most continents also by JSBACH-standard with the exception of Australia where the burned fraction of JSBACH-standard shows almost no variability ~~.~~ (Figure 4).

Surprisingly the observations show a higher Spearman correlation between tree cover and precipitation than the models (Table 1). The lower correlation of the modelled relationship most likely originates from the lower precipitation regions (< 500 mm year^{-1}), where the maximum tree cover is very low in the observations and both models strongly overestimate the maximum tree cover (Figure 4).

Models and observations generally agree on the absence of fire for very high tree cover (>0.8) and on the decrease of burned fraction for mean annual precipitation decreasing below 1000mm. However for regions with tree cover < 0.8 and mean annual precipitation > 1000mm we find strong differences. JSBACH-SPITFIRE ~~has a stronger relationship between low tree cover and high fire occurrence than the observations . In~~ shows a strong negative Spearman rank correlation between burned fraction and tree cover, the observations show a weaker negative correlation, and JSBACH-standard shows a positive correlation (Table

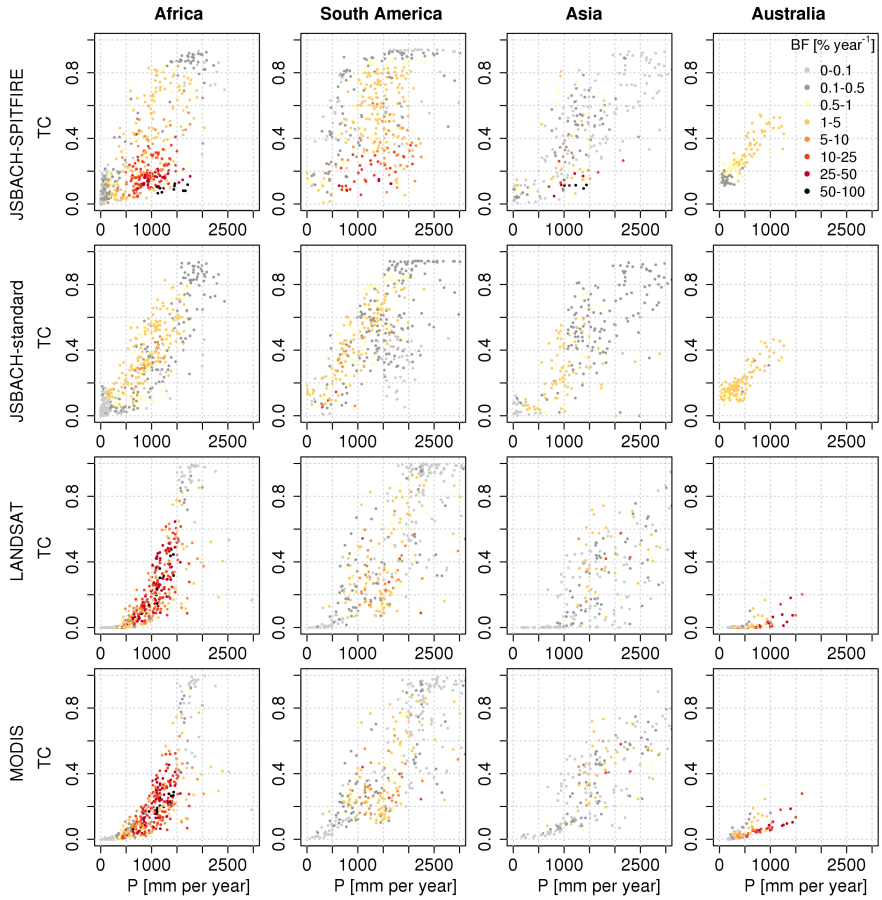

Figure 4. Modelled and observed tree cover (TC) versus precipitation (P), color coded burned area fraction (BF). Satellite datasets were aggregated to model grid resolution (1.875°).

1). This can also be seen in Figure 4 where for the JSBACH-SPITFIRE simulation the highest burned fractions (> 50% of grid cells year^{-1}) are found in Africa for the lowest tree covers (0.1) and for precipitation between 1000-2000 mm year^{-1}~~(Figure 4). The observations show similar values of the burned fraction for tree cover values up to 0.3 for MODIS and up to 0.5 for LANDSAT~~. JSBACH-standard in many grid cells shows low fire occurrence for low tree cover, especially for South America (Figure 4), these grid cells have a high fraction of crops or pasture, which both are excluded from burning in JSBACH-standard (in SPITFIRE only crops are excluded). The observations (also Figure 4) show highest values of the burned fraction for tree cover values up to 0.3 for MODIS and up to 0.5 for LANDSAT.

Burned fraction is much lower in Asia and South America compared to Australia and Africa in the observations. Both models show an underestimation of the fire occurrence in Australia. SPITFIRE reproduces the ~~strong fire regime~~ fire regime with high annual burned fraction in Africa. In JSBACH-standard the difference in burned fraction between the continents is smaller than

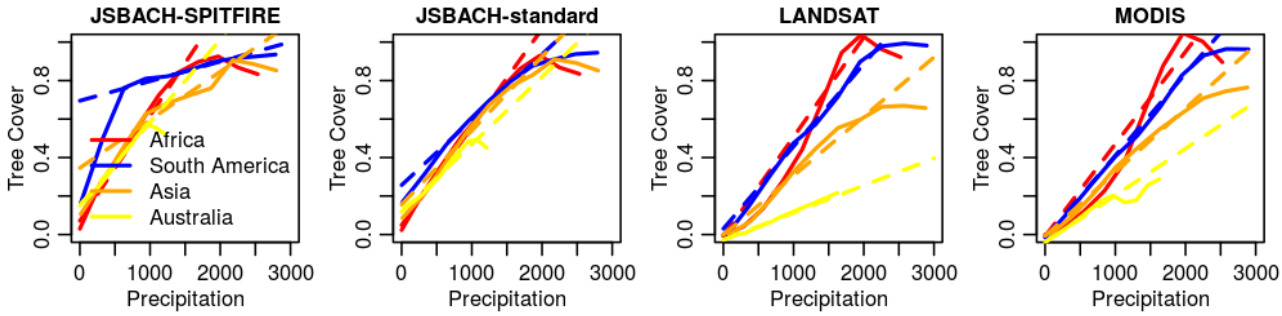

Figure 5. Modelled and observed relatioship between precipitation and maximum tree cover based on a linear quantile regression (dashed line) and a local quantile regression (solid line). Different colors indicate the different continents.

in JSBACH-SPITFIRE (Figure 4).

Models and observations show differences between continents in the relationship between precipitation and ~~tree cover~~maximum tree cover (Figure 5). For Africa, South America and Asia the relationship between maximum tree cover and precipiation shows a saturation for high precipitation. For Australia maximum tree cover increases linearly with increasing precipitation for models and observations~~. For the other three continents in the observations the tree cover increase has a sigmoid shape with a saturation for high precipitation~~, but the precipitation range also does not reach values where a clear saturation is reached for the other continents. For JSBACH-standard the ~~increase in maximum tree cover is linear but also saturates, the increase in~~ curves are very similar for the different continents. JSBACH-SPITFIRE ~~more closely resembles the sigmoid shape of the satellite observations. Surprisingly the observations show a higher Spearman correlation between tree cover and precipitation than the models (Table 1). The lower correlation of the modelled relationship most likely originates from the lower precipitation regions, where the maximum tree cover is very low in the observations and models strongly overestimate the maximum tree cover~~ shows a stronger variation, this must be due to the differences in fire as the model is otherwise the same. The observations show an even stronger variation between continent, with clearly lower tree cover valuse for Australia followed by Asia. For Africa local quantile regression clearly differs from the linear quantile regression for the satellite data, indicating a sigmoid shape, while the other continents show a rather linear increase until the saturation (Figure 5). JSBACH-SPITFIRE reproduces the higher tree cover for South America compared to Africa (albeit the difference is stronger) for mean annual precipitation lower than 1000 mm, but also JSBACH-standard shows a small difference.

The grass cover has a much higher variability in the model compared to the MODIS data (Figure 6). The modelled non-vegetated fraction decreases faster with increasing precipitation compared to the observations (Figure 6). The dominance of trees (computed as TC/total vegetation cover) is strongly overestimated in the model for low precipitation (<500 mm year^{-1}, Figure 6). While the relationship between precipitation and non-vegetated fraction is similar between the continents, the relationship for grass cover differs (Figure 6). For Australia observations and modelled grass cover increases with increasing precipitation. In Africa, South America and Asia grass cover first increases and then decreases with increasing precipitation.

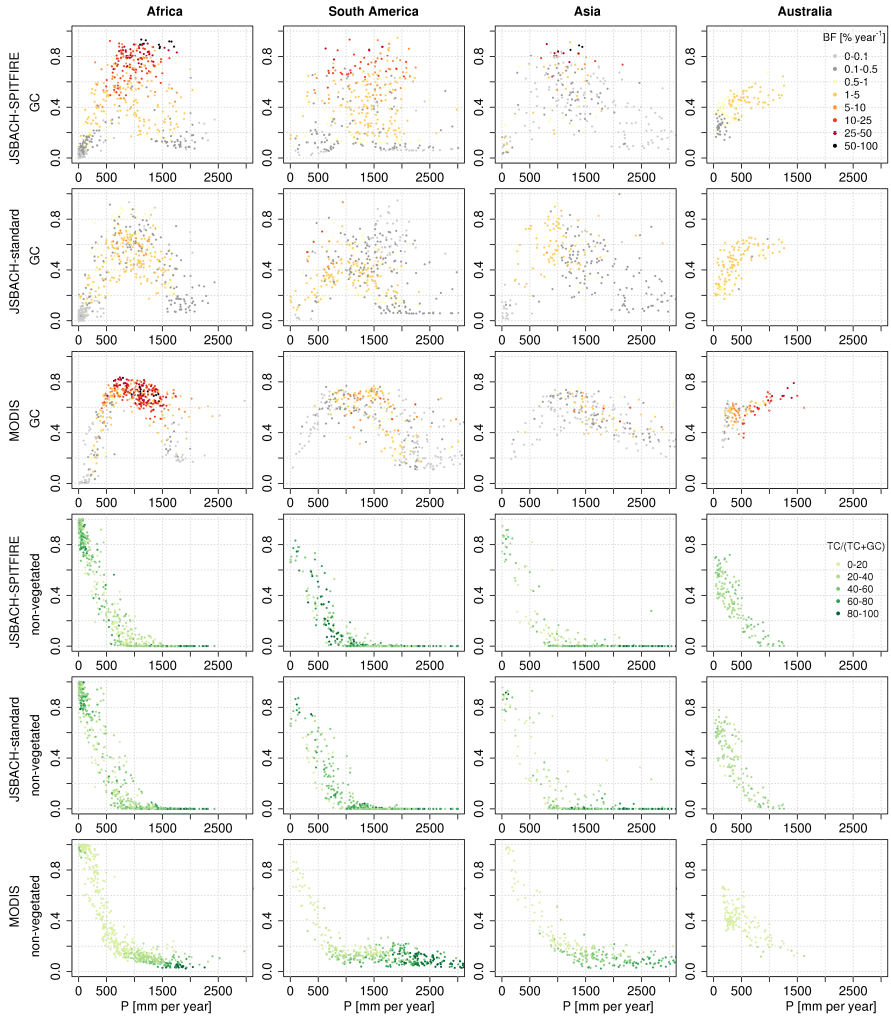

Figure 6. Modelled and observed grass cover (GC) and non-vegetated fraction over precipitation (P), with color coded burned area fraction (BF) for the grass cover and dominance of trees as (TC/total vegetation cover) for the non-vegetated fraction.

3.4 Climate-fire-vegetation relationships: Influences of land use change

The simulation with preindustrial land use represents a state with low influence of land use change. The comparison to the historical simulation allows to assess the influence of land use change since 1850. The impact of fire on tree cover, as quantified by the Spearman rank correlation, between burned fraction and tree cover is higher for the simulation with preindustrial land use (Table 1). Land use change did not affect the rank correlation between precipitation and tree cover. The precipitation range for 80% of the burned area is only slightly narrower for the simulation including land use change (Table 1). Tree cover, however, is even higher for low precipiation and reaches canopy closure for lower precipitation (Table 1 and Figure 7 compared to Figure

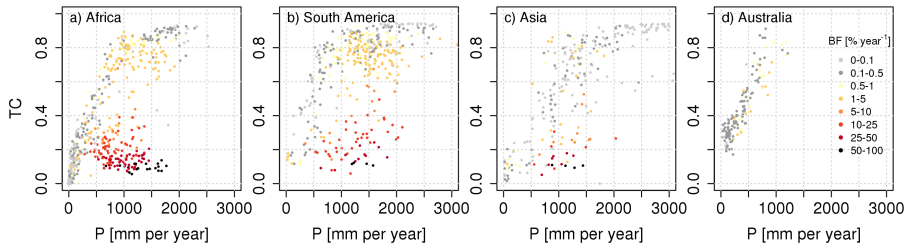

Figure 7. Same as Figure 4 for JSBACH-SPITFIRE but with preindustrial land use.

4). The simulation with land use of 1850 shows a strong gap between the savanna systems (TC < 40%) and closed forests (TC > 70%) for Africa and less strong for South America (Figure 7). For Australia and Asia the simulation does not show this pattern. ~~For~~ In the historical simulation land use overprints this ~~pattern~~ gap of the natural vegetation dynamics. The difference in fire occurrence between Africa and South America is smaller for the simulation with preindustrial land use compared to the historical simulation (Figure 7 compared to Figure 4).

4 Discussion

The multivariate model-data comparison identified differences and agreements between modelled and observed interactions between fire, vegetation and climate. It goes beyond spatial comparisons by providing better guidance on which processes in the model need improvement. ~~We here~~ Here we discuss which model improvements can help to address the differences, what causes agreements in intercontinental differences and whether limitations of the observations might influence our findings.

4.1 Opportunities for model improvements

JSBACH overestimates tree cover for low precipitation on all tropical continents. In these dry regions no or only very low burned fractions are observed, and ~~the fire models show~~ SPITFIRE shows a good response to precipitation while JSBACH-standard already overestimates the burned area (Figure 3). ~~Improvements in the fire model can therefore not improve this mismatch~~The improved burned area pattern of SPITFIRE did not lead to an improvement in tree cover for these dry regions. It is therefore unlikely that further improvements in burned fraction will improve this model-data mismatch for tree cover in dry regions, satellite data however indicate that the intensity of fires increases in these regions and might help to explain the disappearance of trees (Hantson et al., 2017). The mechanisms however are not sufficiently understood to be included in a model. The productivity of vegetation in the JSBACH model depends on the availability of water and is therefore sensitive to drought. The establishment time scale of trees, however, is a constant (30 years for tropical PFTs) and only if a 5 year average of NPP turns negative, drought effects on the dynamic vegetation take effect. Other models require a minimum of 100 mm year^{-1} precipitation for sapling establishment (Sitch et al., 2003). The ~~too high~~ excessive tree cover could be partly improved by improving

the non-vegetated fraction which decreases too fast with increasing precipitation. The ~~too high~~ excessive dominance of trees (Figure 5) however indicates that also the tree-grass competition is not well represented in the model. Tree-grass competition for water could for example be improved in the model by introducing ~~the~~ a sapling stage of trees, which are competitively inferior to grasses (D'Onofrio et al., 2015). Including this mechanism could improve the balance between tree and grass cover, but it could also reduce the establishment rate of trees and therefore, the tree cover in the dry regions with excessive tree cover. Including a PFT-specific rooting depth of vegetation would be an important extension of the model to improve the competition for water between grasses, saplings and adult trees.

The absence of fire for closed canopies is captured well by JSBACH-SPITFIRE, the modelled strong relationship between higher burned fraction and lower tree cover for open canopies (Figure 4, with the exception of Australia, Table 1), however, is not found in the observations (Figure 2,4,Table 1). Many general processes determining the savanna-forest boundary are included in the JSBACH-SPITFIRE model: Increased tree cover leads to a suppression of fire by excluding grasses, higher flammability of grasses leads to increases in fire occurrence with increasing grass biomass (Hoffmann et al., 2012). In JSBACH-SPITFIRE bark thickness is PFT specific and depends on the biomass. Tropical trees are represented by two PFTs one of them has a lower sensitivity to fire due to a higher bark thickness and a higher stem leading to a lower probability of crown scorch. This is also observed in field studies where savanna species show a higher ratio of bark thickness to stem diameter (Hoffmann et al., 2003). Inclusion or improvement of several ecological processes might improve the modelled relationship. Bark thickness is a key property of trees for the fire-related mortality. In JSBACH-SPITFIRE bark thickness is PFT specific and depends on the biomass. The adaptation of trees to frequent fires by increased bark thickness, and therefore higher resistance of trees to fire (Pellegrini et al., 2017) would increase the tree cover in regions with high burned fraction. This could be implemented in the model with more specific PFTs or by modifying the bark thickness according to the fire regime. Kelley and Harrison (2014) included bark thickness as an adaptive trait in the LPX model, which increased and improved the tree cover for Australia. Resprouting is another important mechanism that changes the balance between mortality and recovery and also leads to an increase in tree cover in fire affected areas in a modelling study (Kelley and Harrison, 2014). A second option to decrease the strong associating between high burned area and tree cover could be a negative feedback between fire occurrence and tree mortality: frequent fire occurrence leads to low fuel loads and low fuel loads allow only low intensity fires with associated lower mortality of trees. ~~This feedback~~ In consequence a high burning frequency could lead to lower tree mortality and therefore higher tree cover. This feedback between fire, fuel load, fire intensity and tree mortality is included in the SPITFIRE model, but might be too weak ~~.~~ and therefore result in the stronger correlation between burned fraction and tree cover (Table 1).

A more detailed representation of vegetation structure including a sapling state of trees that is more sensitive to fire (e.g. Higgins et al., 2000) and a ~~long lived~~ long-lived adult tree state could also increase the survival of trees. The "fire trap" describes a mechanism where in regions with frequent fires topkill of saplings maintains them in a nonreproductive state (Hoffmann et al., 2009). It explains the importance of the fire free intervals to allow accumulation of sufficient bark to gain sufficient fire resistence. The JSBACH model does not represent the age structure of vegetation, therefore fire always affects the average tree while in reality only trees that did not accumulate sufficient bark are affected (Hoffmann et al., 2012). Moreover,

fire does not influence the tree establishment in JSBACH, it can only lead to mortality.

For Australia underestimation of burned area for both fire models is strong (Figure 4). In a previous evaluation where the model was forced with observed climate and vegetation cover was prescribed (in contrast to the dynamic vegetation cover and climate modelled by the MPI-ESM) JSBACH-SPITFIRE showed better results for Australia (Hantson et al., 2015). An improved response of vegetation cover dynamics to precipitation will therefore likely improve the patterns of burned area.

The rank correlation between precipitation and tree cover is higher for the observations compared to the model outputs (Table 1). One reason might be the lower maximum tree cover for low precipitation in the observations which limits the range of tree cover values in these regions. In JSBACH-standard the correlation between tree cover and precipitation is stronger than in JSBACH-SPITFIRE. In the JSBACH-standard model, fire is only driven by meteorological variables and vegetation properties (which also largely follow climatic gradients). JSBACH-SPITFIRE, however, also uses population density and lightning datasets as input, which are potentially inconsistent with the meteorological forcing derived from the MPI-ESM output. This decoupling between climate and ignitions might cause the lower correlation for JSBACH-SPITFIRE compared to the JSBACH-standard simulation. For instance in the Northeast Amazon region precipitation of the MPI-ESM is too low, leading to a decrease in tree cover in regions with closed canopy with the JSBACH-standard fire model. The very low ignitions in JSBACH-SPITFIRE in that region contribute to a low fire occurrence compared to JSBACH-standard and in consequence to higher tree cover (Figure 1). Lightning can be computed within climate models (Krause et al., 2014) and using these lightning datasets based on the model not on observations would ensure consistency between meteorological forcing and the ignitions used in the fire model (Felsberg et al., 2018).

How exactly these plausible modifications would change the patterns of tree cover, fire and their relation to climate likely strongly depends on the exact parameterization and needs to be tested with stepwise model development and factorial simulations. Many climate models have problems to represent extremes, length of dry periods and tend to generate a permanent drizzle (DeAngelis et al., 2013; Gutowski et al., 2003). With our approach we only include mean annual precipitation, other aspects of the modelled climate are neglected but might contribute to model-data mismatches in the relationship between precipitation and other variables. Mean annual precipitation is however a strong driver of vegetation patterns especially in the tropics and including more climate parameters would require an entirely different approach and possibly limit visualization and interpretation of the results. Including more climatic parameters could especially help to interpret more of the variability for mean annual precipitation amounts that allow tree establishment but do not lead to complete canopy closure. The reasonable relationship of mean annual precipitation and burned area however indicates either, that additional climate biases are not important as fire is quite sensitive to the length of dry seasons, or that the fire model cancels out additional climate biases.

4.2 Difference between continents

We find differences in the climate-vegetation-fire relationships between continents in the satellite products as well as in the model simulations with JSBACH-SPITFIRE and the JSBACH standard model. Differences in the climate-vegetation-fire relationships have been described based on site level datasets (Lehmann et al., 2014). They find that the response of tree basal area to growth conditions (climate and nutrients) and disturbances differs between continents. The study suggests that the

one climate–one vegetation paradigm which is an under-pinning of many global vegetation models cannot lead to vegetation patterns that differ between continents under the same climatic conditions as the patterns depend on past environmental conditions and evolution. Evolution is not accounted for in common vegetation models. In simulations with changing climatic forcing, however, the vegetation is a function of previous environmental conditions and adapts to changes in climate with ~~usually~~ constant PFT specific time scales. Additionally the human dimension is more and more included in DGVMs, primarily by including anthropogenic land cover change. Moreover, in recent global fire models population density is a commonly used driver ~~(Hantson et al., 2016).~~ for human ignitions and suppression of fires (Hantson et al., 2016).

Our model simulations show that also ~~the modelled~~ global vegetation models models can have differences in climate-vegetation-fire relationships ~~differ~~ between continents. ~~The simulations show a saturation in tree cover for higher precipitation for Africa, South America and Asia, but a linear increase for Australia. Site level observations show the same difference for tree basal area and effective rainfall (Lehmann et al., 2014). In the model this difference is not affected by land use and not by the type of fire model, it is therefore rather a result of different climate, maybe seasonality that is not resolved by the mean annual precipitation. We confirmed in the factorial simulation~~ We seperated the effect of land use change by comparing the historical simulation to a simulation with preindustrial land use. We find that land cover change is influencing the differences in the modelled fire regime between Africa and South America. Land cover change influences simulated fire occurrence as cropland areas are excluded from burning and pastures have a higher fuel bulk density in the JSBACH-SPITFIRE model. A reduction in ~~fire occurrence~~ burned area due to increases in croplands is well supported by statistical analysis of satellite data for Africa (Andela and van der Werf, 2014) and globally (Bistinas et al., 2014; Andela et al., 2017). The mechanism behind the reduction in burned area due to croplands is however likely a fragmentation of the landscape, which is not explicitly accounted for in the model. Fragmentation of the landscape by for instance roads, can act as a fire break and therefore reduce the potential fire size. The exact relationships between humans, land use and vegetation fires are still unknown and therefore not well represented in models.

Vegetation in the MPI Earth system model including SPITFIRE is not only a function of climate but also depends on the history of previous vegetation due to the feedback between fire and vegetation (Lasslop et al., 2016). We did not isolate the effect of the multi-stability in this study but initialized the model with the standard vegetation initialization of the MPI-ESM for the year 1850. The SPITFIRE model also takes into account differences in the fire regime through spatially varying ignitions. In addition to the effect of land use on the differences between continents these spatial differences in ignitions might be important and might explain the smaller differences for the purely climate and land use driven JSBACH-standard model.

The comparison of the increase in maximum tree cover with increasing precipiation shows that although the model shows some variability between continents, it misses a large part of the observed variation. Finding the correct balance of the many influencing factors, e.g. climate, fire, land use, evolutionary differences, will remain a challenge for the future.

4.3 Limitations in the comparability between observations and modeled variables

We use two remotely sensed tree cover products, which show coherent patterns. Although these products are derived from imagery with different spectral, temporal and spatial characteristics (MODIS and Landsat), they cannot be considered totally

independent because both are derived using a similar classification and regression tree method as well as reference data. The observational tree cover datasets are limited to trees taller than 5 m and do not include shrubs. For the model however we included shrubs and all trees. Previously differences in the threshold where maximum tree cover is reached were attributed to different precipitation datasets and ex- or inclusion of shrub cover (Devine et al., 2017). Filtering modelled and observed tree cover based on the presence of shrubs in the MODIS land cover product leads to only small differences in the relationship between tree cover and precipitation (Figure A1). Excluding grid cells where biomass indicates that the vegetation height is smaller than 5 m according to the allometric relationship used in SPITFIRE-JSBACH (Lasslop et al., 2014) did not lead to substantially different relationships (Figure A2). Our conclusions are therefore not affected by the limitation of the datasets to observe only trees taller than 5 m.

Compared to the satellite datasets, an African site level dataset shows lower thresholds of precipitation for the absence of trees (ca. 100 mm year^{-1}) and for reaching the highest tree cover values (>650 mm year^{-1}) (Sankaran et al., 2005). The remote sensing datasets show for Africa an absence of tree cover for precipitation less than ca. 300 mm and canopy closure for 1500 mm year^{-1} in the model resolution (Figure 4). However, the general absence of trees for very low precipitation and increase until a certain threshold is similar to the remote sensing datasets.

The maximum value of a variable can decrease due to spatial averaging. We tested this effect by not using the mean when aggregating the satellite tree cover to the resolution of the precipitation dataset but instead using the maximum value of the underlying 0.05° grid cells of tree cover. Canopy closure can then be reached for all continents for mean precipitation values around 500-1000 mm year^{-1} (Figure A3), which is more consistent with a published site level dataset (Sankaran et al., 2005). This is consistent with the figures in ~~Hirota et al. (2011)~~ (Hirota et al., 2011) where the MODIS tree cover is shown in 1km resolution. The scale at which maximum tree covers are observed and the spatial scale of the model application therefore needs to be considered. Moreover, as the thresholds found for the model are closer to the ones found for site-level and high resolution satellite datasets the model performance could improve if the spatial resolution of the model is increased.

Tree cover seems to be a clearly defined variable, but already varies between the two satellite datasets, the MODIS tree cover dataset defines a maximum tree cover of 80%, while the LANDSAT tree cover dataset allows a cover of 100%. In the ~~model,~~ observations not fully closed canopies due to low foliar biomass might be tracked as a reduced tree cover. In the model, however, tree cover and biomass are two rather independent variables, meaning that tree cover can be high in spite of a low biomass. ~~In the observations not fully closed canopies due to low foliar biomass might be tracked as a reduced tree cover.~~ Biomass datasets might therefore give additional valuable insights and pan-tropical datasets are available (Saatchi et al., 2011; Baccini et al., 2012; Avitabile et al., 2016).

The latest release of the GFED burned area and emissions datasets includes an extension for small fires (Randerson et al., 2012). However these small fires are often related to cropland fires or deforestation fires. Neither of these fire types are modelled explicitely in our model approaches and therefore could cause an unwanted mismatch. Cropland fires are not expected to strongly influence the vegetation cover, while deforestation is prescribed as described in the model and simulation paragraphs and therefore the influence on vegetation cover is considered. Burned area datasets are generally uncertain mainly due to the limited spatial and temporal resolution (Padilla et al., 2015), the difference in global burned area between the dataset including

small fires and the one not including small fires is 25%. The spatial patterns are less affected, but missed burned areas due to high cloud cover certainly introduces also spatial biases. How important such errors are for a comparison as present here is unknown.

5 Conclusions

This study combines two satellite datasets with model simulations using a simple and a complex fire algorithm to investigate relationships between fire, vegetation and climate. Our analysis shows that the two satellite datasets are consistent in terms of the relationship between tree cover, precipitation and fire occurrence, but the spatial scale needs to be considered as some statistical characteristics change with the resolution.

Our analysis showed the strength of the multivariate comparison to detect model inconsistencies and guide model development. It goes beyond the insights gained by standard spatial comparisons. For JSBACH, independent of the fire model used, we find an overestimation of tree cover for low precipitation where typically fire occurrence is low due to limited fuel availability. The response of burned area to precipitation was captured well for SPITFIRE, but the simple fire scheme showed an overestimation of burned area for dry regions. This indicates that not an improvement of the fire model but improved modelling of drought effects on the vegetation dynamics will improve the response of vegetation to climate in dry regions. Dry regions often show a strong coupling between land and atmosphere (Koster et al., 2006), such an improvement has therefore also a high potential to improve the performance of the coupled Earth system model.

While fire occurrence and vegetation patterns are well observed by remote sensing, the impact of fire on vegetation is much less constrained by satellite observations limiting the possibilities of evaluating that part of fire models. The multivariate comparison ~~helped to identify~~ revealed a too strong ~~effect~~ impact of fire on tree cover ~~,~~ for gridcells with very high fire occurrence, which leads to too low tree cover. To boost the tree cover in exactly these regions with high fire occurrence possible model modifications are an adaptation of trees to fire, by increasing bark thickness in reponse to high fire frequencies, or a stronger negative feedback between fire occurrence and fuel load~~are possible model improvements~~. This stronger feedback should then reduce fire intensity and consequently fire mortality.

The complex fire model SPITFIRE improves the difference in fire regimes between the continents, especially Africa and South America, compared to the simple fire model. The ~~factorial model simulation shows that anthropogenic land use contributes to differences in burned area between the continents in the JSBACH-SPITFIRE model. Our~~ intercontinental variation in the relationship between precipitation and maximum tree cover is much smaller for the models compared to the observations. Known variations in vegetation are not sufficiently understood to be represented in models. However, our finding that models do show differences in the fire-vegetation-climate relationships between continents shows that ~~although known variations in vegetation characteristics are not represented in models , they~~ further exploration why models show differences can be helpful to better understand causes for intercontinental differences.

Overall the multivariate model evaluation highlights the potential for more targeted model improvements with respect to the

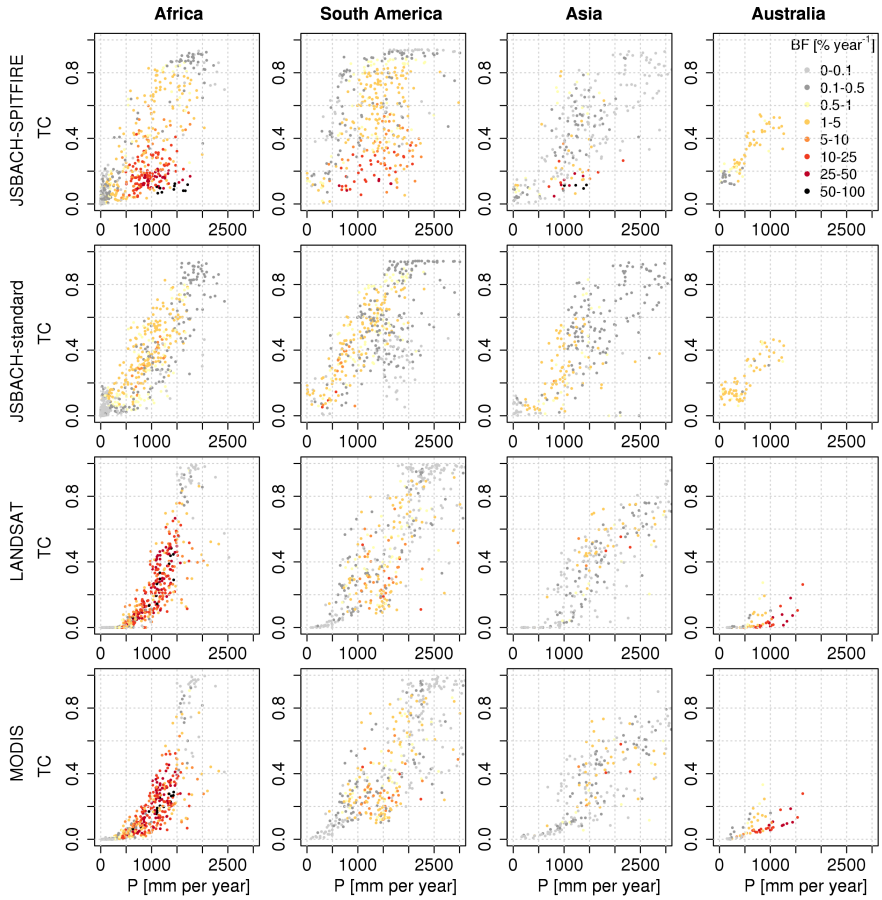

Figure A1. Same as figure 4 but tree cover filtered for the presence of shrub lands (using the MODIS open and closed shrub land classification). This indicates a low sensitivity of the fire-vegetation-climate relationships to shrub lands.

interactions between climate, vegetation and fire, which are crucial for our understanding of future vegetation projections.

Code and data availability. The observational datasets are freely available. The processed data and model output as displayed in this publication and the processing scripts are available upon request to publications@mpimet.mpg.de.

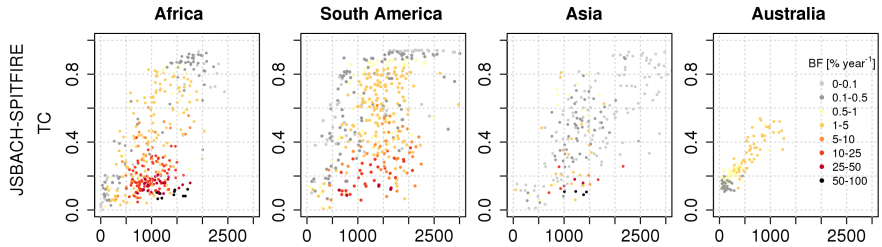

Figure A2. Modelled tree cover (TC) versus precipitation (P) [mm year-1]. Modelled tree cover was filtered for vegetation height of trees <5 m using the modelled vegetation height. This value is given as detection threshold for the satellite products. When filtering the model output with this threshold the differences to the unfiltered dataset are very small (compare with Figure 4, panels for JSBACH-SPITFIRE).

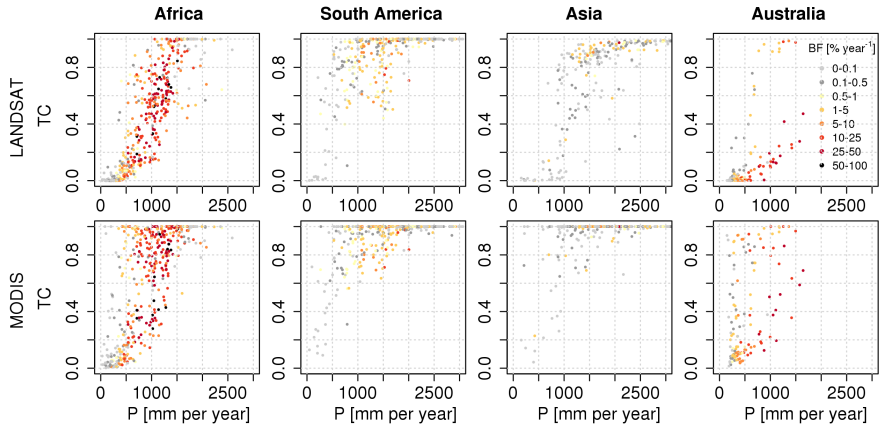

Figure A3. Tree cover (TC) versus precipitation (P) with color coded burned fraction (BF). Tree cover was here remapped from 0.05° resolution to 2° using the maximum value of the higher resolution instead of the mean.

Appendix A: Sensitivity of climate-vegetation-fire relationships to remapping, presence of shrubs and modelled tree height

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References

Alkama, R. and Cescatti, A.: Biophysical climate impacts of recent changes in global forest cover, Science (80-.)., 351, 600–604, https://doi.org/10.1126/science.aac8083, http://www.sciencemag.org/cgi/doi/10.1126/science.aac8083, 2016.

Andela, N. and van der Werf, G. R.: Recent trends in African fires driven by cropland expansion and El Niño to La Niña transition, Nat. Clim. Chang., 4, 791–795, https://doi.org/10.1038/nclimate2313, http://www.nature.com/doifinder/10.1038/nclimate2313, 2014.

Andela, N., Morton, D. C., Giglio, L., Chen, Y., van der Werf, G. R., Kasibhatla, P. S., DeFries, R. S., Collatz, G. J., Hantson, S., Kloster, S., Bachelet, D., Forrest, M., Lasslop, G., Li, F., Mangeon, S., Melton, J. R., Yue, C., and Randerson, J. T.: A human-driven decline in global burned area, Science (80-.)., 356, 1356–1362, http://science.sciencemag.org/content/356/6345/1356.abstract, 2017.

Avitabile, V., Herold, M., Heuvelink, G. B. M., Lewis, S. L., Phillips, O. L., Asner, G. P., Armston, J., Ashton, P. S., Banin, L., Bayol, N., Berry, N. J., Boeckx, P., de Jong, B. H. J., DeVries, B., Girardin, C. A. J., Kearsley, E., Lindsell, J. A., Lopez-Gonzalez, G., Lucas, R., Malhi, Y., Morel, A., Mitchard, E. T. A., Nagy, L., Qie, L., Quinones, M. J., Ryan, C. M., Ferry, S. J. W., Sunderland, T., Laurin, G. V., Gatti, R. C., Valentini, R., Verbeeck, H., Wijaya, A., and Willcock, S.: An integrated pan-tropical biomass map using multiple reference datasets, Glob. Chang. Biol., 22, 1406–1420, https://doi.org/10.1111/gcb.13139, http://doi.wiley.com/10.1111/gcb.13139, 2016.

Baccini, A., Goetz, S. J., Walker, W. S., Laporte, N. T., Sun, M., Sulla-Menashe, D., Hackler, J., Beck, P. S. A., Dubayah, R., Friedl, M. A., Samanta, S., and Houghton, R. A.: Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps, Nat. Clim. Chang., 2, 182–185, https://doi.org/10.1038/nclimate1354, http://www.nature.com/articles/nclimate1354, 2012.

Bathiany, S., Claussen, M., Brovkin, V., Raddatz, T., and Gayler, V.: Combined biogeophysical and biogeochemical effects of large-scale forest cover changes in the MPI earth system model, Biogeosciences, 7, 1383–1399, https://doi.org/10.5194/bg-7-1383-2010, http://www.biogeosciences.net/7/1383/2010/, 2010.

Baudena, M., Dekker, S. C., van Bodegom, P. M., Cuesta, B., Higgins, S. I., Lehsten, V., Reick, C. H., Rietkerk, M., Scheiter, S., Yin, Z., Zavala, M. A., and Brovkin, V.: Forests, savannas, and grasslands: bridging the knowledge gap between ecology and Dynamic Global Vegetation Models, Biogeosciences, 12, 1833–1848, https://doi.org/10.5194/bg-12-1833-2015, http://www.biogeosciences.net/12/1833/2015/, 2015.

Bistinas, I., Harrison, S. P., Prentice, I. C., and Pereira, J. M. C.: Causal relationships versus emergent patterns in the global controls of fire frequency, Biogeosciences, 11, 5087–5101, https://doi.org/10.5194/bg-11-5087-2014, 2014.

Bonan, G. B.: Forests and climate change: forcings, feedbacks, and the climate benefits of forests., Science (80-.)., 320, 1444–9, https://doi.org/10.1126/science.1155121, http://www.ncbi.nlm.nih.gov/pubmed/18556546, 2008.

Brovkin, V., Claussen, M., Petoukhov, V., and Ganopolski, A.: On the stability of the atmosphere-vegetation system in the Sahara/Sahel region, J. Geophys. Res., 103, 31 613, https://doi.org/10.1029/1998JD200006, http://doi.wiley.com/10.1029/1998JD200006, 1998.

Brovkin, V., Raddatz, T., Reick, C. H., Claussen, M., and Gayler, V.: Global biogeophysical interactions between forest and climate, Geophys. Res. Lett., 36, 1–6, https://doi.org/10.1029/2009GL037543, http://www.agu.org/pubs/crossref/2009/2009GL037543.shtml, 2009.

DeAngelis, A. M., Broccoli, A. J., and Decker, S. G.: A Comparison of CMIP3 Simulations of Precipitation over North America with Observations: Daily Statistics and Circulation Features Accompanying Extreme Events, J. Clim., 26, 3209–3230, https://doi.org/10.1175/JCLI-D-12-00374.1, http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-12-00374.1, 2013.

Devine, A. P., McDonald, R. A., Quaife, T., and Maclean, I. M. D.: Determinants of woody encroachment and cover in African savannas, Oecologia, 183, 939–951, https://doi.org/10.1007/s00442-017-3807-6, http://link.springer.com/10.1007/s00442-017-3807-6, 2017.

D'Onofrio, D., Baudena, M., D'Andrea, F., Rietkerk, M., and Provenzale, A.: Tree-grass competition for soil water in arid and semiarid savannas: The role of rainfall intermittency, Water Resour. Res., 51, 169–181, https://doi.org/10.1002/2014WR015515, http://doi.wiley.com/10.1002/2014WR015515, 2015.

Felsberg, A., Kloster, S., Wilkenskjeld, S., Krause, A., and Lasslop, G.: Lightning Forcing in Global Fire Models: The Importance of Temporal Resolution, J. Geophys. Res. Biogeosciences, https://doi.org/10.1002/2017JG004080, http://doi.wiley.com/10.1002/2017JG004080, 2018.

Friedl, M. A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., and Huang, X.: MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets, Remote Sens. Environ., 114, 168–182, https://doi.org/10.1016/j.rse.2009.08.016, http://linkinghub.elsevier.com/retrieve/pii/S0034425709002673, 2010.

Gerard, F., Hooftman, D., van Langevelde, F., Veenendaal, E., White, S. M., and Lloyd, J.: MODIS VCF should not be used to detect discontinuities in tree cover due to binning bias. A comment on Hanan et al. (2014) and Staver and Hansen (2015), Glob. Ecol. Biogeogr., 26, 854–859, https://doi.org/10.1111/geb.12592, http://dx.doi.org/10.1111/geb.12592, 2017.

Giglio, L., Randerson, J. T., and van der Werf, G. R.: Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4), J. Geophys. Res. Biogeosciences, 118, 317–328, https://doi.org/10.1002/jgrg.20042, http://doi.wiley.com/10.1002/jgrg.20042, 2013.

Giorgetta, M. A., Jungclaus, J., Reick, C. H., Legutke, S., Bader, J., Böttinger, M., Brovkin, V., Crueger, T., Esch, M., Fieg, K., Glushak, K., Gayler, V., Haak, H., Hollweg, H.-D., Ilyina, T., Kinne, S., Kornblueh, L., Matei, D., Mauritsen, T., Mikolajewicz, U., Mueller, W., Notz, D., Pithan, F., Raddatz, T., Rast, S., Redler, R., Roeckner, E., Schmidt, H., Schnur, R., Segschneider, J., Six, K. D., Stockhause, M., Timmreck, C., Wegner, J., Widmann, H., Wieners, K.-H., Claussen, M., Marotzke, J., and Stevens, B.: Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase 5, J. Adv. Model. Earth Syst., 5, 572–597, https://doi.org/10.1002/jame.20038, http://doi.wiley.com/10.1002/jame.20038, 2013.

Gutowski, W. J., Decker, S. G., Donavon, R. A., Pan, Z., Arritt, R. W., and Takle, E. S.: Temporal–Spatial Scales of Observed and Simulated Precipitation in Central U.S. Climate, J. Clim., 16, 3841–3847, https://doi.org/10.1175/1520-0442(2003)016<3841:TSOOAS>2.0.CO;2, http://journals.ametsoc.org/doi/abs/10.1175/1520-0442{%}282003{%}29016{%}3C3841{%}3ATSOOAS{%}3E2.0.CO{%}3B2, 2003.

Hagemann, S., Loew, A., and Andersson, A.: Combined evaluation of MPI-ESM land surface water and energy fluxes, J. Adv. Model. Earth Syst., pp. n/a–n/a, https://doi.org/10.1029/2012MS000173, http://doi.wiley.com/10.1029/2012MS000173, 2013.

Hansen, M. C., DeFries, R. S., Townshend, J. R. G., Carroll, M., Dimiceli, C., and Sohlberg, R. a.: Global Percent Tree Cover at a Spatial Resolution of 500 Meters: First Results of the MODIS Vegetation Continuous Fields Algorithm, Earth Interact., 7, 1–15, https://doi.org/10.1175/1087-3562(2003)007<0001:GPTCAA>2.0.CO;2, http://journals.ametsoc.org/doi/abs/10.1175/1087-3562(2003)007{%}3C0001:GPTCAA{%}3E2.0.CO;2, 2003.

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. a., Tyukavina, A., Thau, D., Stehman, S. V., Goetz, S. J., Loveland, T. R., Kommareddy, A., Egorov, A., Chini, L., Justice, C. O., and Townshend, J. R. G.: High-resolution global maps of 21st-century forest cover change., Science, 342, 850–3, https://doi.org/10.1126/science.1244693, http://www.ncbi.nlm.nih.gov/pubmed/24233722, 2013.

Hantson, S., Lasslop, G., Kloster, S., and Chuvieco, E.: Anthropogenic effects on global mean fire size, Int. J. Wildl. Fire, 24, 589–596, https://doi.org/10.1071/WF14208, http://www.publish.csiro.au/?paper=WF14208, 2015.

Hantson, S., Arneth, A., Harrison, S. P., Kelley, D. I., Prentice, I. C., Rabin, S. S., Archibald, S., Mouillot, F., Arnold, S. R., Artaxo, P., Bachelet, D., Ciais, P., Forrest, M., Friedlingstein, P., Hickler, T., Kaplan, J. O., Kloster, S., Knorr, W., Lasslop, G., Li, F., Mangeon, S., Melton, J. R., Meyn, A., Sitch, S., Spessa, A., van der Werf, G. R., Voulgarakis, A., and Yue, C.: The status and challenge of global fire

modelling, Biogeosciences Discuss., pp. 1–30, https://doi.org/10.5194/bg-2016-17, http://www.biogeosciences-discuss.net/bg-2016-17/, 2016.

Hantson, S., Scheffer, M., Pueyo, S., Xu, C., Lasslop, G., van Nes, E. H., Holmgren, M., and Mendelsohn, J.: Rare, Intense, Big fires dominate the global tropics under drier conditions, Sci. Rep., 7, 14 374, https://doi.org/10.1038/s41598-017-14654-9, http://www.nature.com/articles/s41598-017-14654-9, 2017.

Higgins, S. I. and Scheiter, S.: Atmospheric CO2 forces abrupt vegetation shifts locally, but not globally, Nature, 488, 209–212, https://doi.org/10.1038/nature11238, http://www.nature.com/doifinder/10.1038/nature11238, 2012.

Higgins, S. I., Bond, W. J., and Trollope, W. S. W.: Fire, resprouting and variability: a recipe for grass–tree coexistence in savanna, J. Ecol., 88, 213–229, https://doi.org/10.1046/j.1365-2745.2000.00435.x, http://dx.doi.org/10.1046/j.1365-2745.2000.00435.x, 2000.

Hirota, M., Holmgren, M., Van Nes, E. H., and Scheffer, M.: Global Resilience of Tropical Forest and Savanna to Critical Transitions, Science (80-.)., 334, 232–235, https://doi.org/10.1126/science.1210657, http://www.sciencemag.org/cgi/doi/10.1126/science.1210657, 2011.

Hoffmann, W. a., Orthen, B., and Vargas Do Nascimento, P. K.: Comparative fire ecology of tropical savanna and forest trees, Funct. Ecol., 17, 720–726, https://doi.org/10.1111/j.1365-2435.2003.00796.x, 2003.

Hoffmann, W. A., Adasme, R., Haridasan, M., T. de Carvalho, M., Geiger, E. L., Pereira, M. A. B., Gotsch, S. G., and Franco, A. C.: Tree topkill, not mortality, governs the dynamics of savanna–forest boundaries under frequent fire in central Brazil, Ecology, 90, 1326–1337, https://doi.org/10.1890/08-0741.1, http://doi.wiley.com/10.1890/08-0741.1, 2009.

Hoffmann, W. a., Geiger, E. L., Gotsch, S. G., Rossatto, D. R., Silva, L. C. R., 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, 759–68, https://doi.org/10.1111/j.1461-0248.2012.01789.x, http://www.ncbi.nlm.nih.gov/pubmed/22554474, 2012.

Huffman, G., Adler, R., Bolvin, D., and Nelkin, E.: The TRMM Multi-satellite Precipitation Analysis (TMPA), in: Satell. Rainfall Appl. Surf. Hydrol., edited by Hossain, F. and Gebremichael, M., chap. 1, pp. 3–22, Springer Verlag, 2010.

Huffman, G. J., Bolvin, D. T., Nelkin, E. J., Wolff, D. B., Adler, R. F., Gu, G., Hong, Y., Bowman, K. P., and Stocker, E. F.: The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-Global, Multiyear, Combined-Sensor Precipitation Estimates at Fine Scales, J. Hydrometeorol., 8, 38–55, https://doi.org/10.1175/JHM560.1, http://journals.ametsoc.org/doi/abs/10.1175/JHM560.1, 2007.

Hurtt, G. C., Chini, L. P., Frolking, S., Betts, R. A., Feddema, J., Fischer, G., Fisk, J. P., Hibbard, K., Houghton, R. A., Janetos, A., Jones, C. D., Kindermann, G., Kinoshita, T., Klein Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., Vuuren, D. P., and Wang, Y. P.: Harmonization of land-use scenarios for the period 1500-–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands, Clim. Change, 109, 117–161, https://doi.org/10.1007/s10584-011-0153-2, http://link.springer.com/10.1007/s10584-011-0153-2, 2011.

Kelley, D. I. and Harrison, S. P.: Enhanced Australian carbon sink despite increased wildfire during the 21st century, Environ. Res. Lett., 9, 104 015, https://doi.org/10.1088/1748-9326/9/10/104015, http://stacks.iop.org/1748-9326/9/i=10/a=104015?key=crossref.d09b4fd55bf91ab5f53656426beba387, 2014.

Klein Goldewijk, K., Goldewijk, K. K., and Klein Goldewijk, K.: Estimating global land use change over the past 300 years, Glob. Biogeochem. Cycles, 15, 417–43, http://apps.isiknowledge.com/full{_}record.do?product=UA{&}search{_}mode=GeneralSearch{&}qid=3{&}SID=U2iG6akdAIElMenmoPf{&}page=1{&}doc=2{&}colname=WOS, 2001.

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, 1877–1902, http://www.biogeosciences.net/7/1877/2010/, 2010.

Koenker, R.: quantreg: Quantile Regression, https://cran.r-project.org/package=quantreg, 2018.

Koster, R. D., Sud, Y. C., Guo, Z., Dirmeyer, P. A., Bonan, G., Oleson, K. W., Chan, E., Verseghy, D., Cox, P., Davies, H., Kowalczyk, E., Gordon, C. T., Kanae, S., Lawrence, D., Liu, P., Mocko, D., Lu, C.-H., Mitchell, K., Malyshev, S., McAvaney, B., Oki, T., Yamada, T., Pitman, A., Taylor, C. M., Vasic, R., and Xue, Y.: GLACE: The Global Land–Atmosphere Coupling Experiment. Part I: Overview, J. Hydrometeorol., 7, 590–610, https://doi.org/10.1175/JHM510.1, http://journals.ametsoc.org/doi/abs/10.1175/JHM510.1, 2006.

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, 312–322, https://doi.org/10.1002/2013JG002502, http://doi.wiley.com/10.1002/2013JG002502, 2014.

Krawchuk, M. a. and Moritz, M. a.: Constraints on global fire activity vary across a resource gradient., Ecology, 92, 121–32, http://www.ncbi.nlm.nih.gov/pubmed/21560682, 2011.

Lasslop, G. and Kloster, S.: Impact of fuel variability on wildfire emission estimates, Atmos. Environ., 121, 93–102, https://doi.org/10.1016/j.atmosenv.2015.05.040, http://linkinghub.elsevier.com/retrieve/pii/S1352231015301126, 2015.

Lasslop, G. and Kloster, S.: Human impact on wildfires varies between regions and with vegetation productivity, Environ. Res. Lett., https://doi.org/10.1088/1748-9326/aa8c82, http://iopscience.iop.org/article/10.1088/1748-9326/aa8c82http://iopscience.iop.org/10.1088/1748-9326/aa8c82, 2017.

Lasslop, G., Thonicke, K., and Kloster, S.: SPITFIRE within the MPI Earth system model: Model development and evaluation, J. Adv. Model. Earth Syst., 6, 740–755, https://doi.org/10.1002/2013MS000284, http://doi.wiley.com/10.1002/2013MS000284, 2014.

Lasslop, G., Brovkin, V., Reick, C. H., Bathiany, S., and Kloster, S.: Multiple stable states of tree cover in a global land surface model due to a fire-vegetation feedback, Geophys. Res. Lett., 43, 6324–6331, https://doi.org/10.1002/2016GL069365, http://doi.wiley.com/10.1002/2016GL069365, 2016.

Lehmann, C. E. R., Anderson, T. M., Sankaran, M., Higgins, S. I., Archibald, S., Hoffmann, W. A., Hanan, N. P., Williams, R. J., Fensham, R. J., Felfili, J., Hutley, L. B., Ratnam, J., San Jose, J., Montes, R., Franklin, D., Russell-Smith, J., Ryan, C. M., Durigan, G., Hiernaux, P., Haidar, R., Bowman, D. M. J. S., and Bond, W. J.: Savanna Vegetation-Fire-Climate Relationships Differ Among Continents, Science (80-.)., 343, 548–552, https://doi.org/10.1126/science.1247355, http://www.sciencemag.org/cgi/doi/10.1126/science.1247355, 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, 1345–1360, https://doi.org/10.5194/bg-11-1345-2014, http://www.biogeosciences.net/11/1345/2014/, 2014.

Li, F., Lawrence, D. M., and Bond-Lamberty, B.: Impact of fire on global land surface air temperature and energy budget for the 20th century due to changes within ecosystems, Environ. Res. Lett., 12, 44 014, http://stacks.iop.org/1748-9326/12/i=4/a=044014, 2017.

Mattiuzzi, M. and Detsch, F.: MODIS: Acquisition and Processing of MODIS Products, https://cran.r-project.org/package=MODIS, 2018.

Moncrieff, G. R., Scheiter, S., Bond, W. J., and Higgins, S. I.: Increasing atmospheric CO 2 overrides the historical legacy of multiple stable biome states in Africa, New Phytol., 201, 908–915, https://doi.org/10.1111/nph.12551, http://doi.wiley.com/10.1111/nph.12551, 2014.

Padilla, M., Stehman, S. V., Ramo, R., Corti, D., Hantson, S., Oliva, P., Alonso-Canas, I., Bradley, A. V., Tansey, K., Mota, B., Pereira, J. M., and Chuvieco, E.: Comparing the accuracies of remote sensing global burned area products using stratified random sampling and estimation, Remote Sens. Environ., https://doi.org/10.1016/j.rse.2015.01.005, http://linkinghub.elsevier.com/retrieve/pii/S0034425715000140, 2015.

Pellegrini, A. F. A., Anderegg, W. R. L., Paine, C. E. T., Hoffmann, W. A., Kartzinel, T., Rabin, S. S., Sheil, D., Franco, A. C., and Pacala, S. W.: Convergence of bark investment according to fire and climate structures ecosystem vulnerability to future change, Ecol. Lett., 20, 307–316, https://doi.org/10.1111/ele.12725, http://doi.wiley.com/10.1111/ele.12725, 2017.

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, 1–13, https://doi.org/10.1029/2010GB003906, http://www.agu.org/pubs/crossref/2011/2010GB003906.shtml, 2011.

Rabin, S. S., Melton, J. R., Lasslop, G., Bachelet, D., Forrest, M., Hantson, S., Kaplan, J. O., Li, F., Mangeon, S., Ward, D. S., Yue, C., Arora, V. K., Hickler, T., Kloster, S., Knorr, W., Nieradzik, L., Spessa, A., Folberth, G. A., Sheehan, T., Voulgarakis, A., Kelley, D. I., Prentice, I. C., Sitch, S., Harrison, S., and Arneth, A.: The Fire Modeling Intercomparison Project (FireMIP), phase 1: experimental and analytical protocols with detailed model descriptions, Geosci. Model Dev., 10, 1175–1197, https://doi.org/10.5194/gmd-10-1175-2017, https://www.geosci-model-dev.net/10/1175/2017/, 2017.

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. Geophys. Res. Biogeosciences, 117, G04 012, https://doi.org/10.1029/2012JG002128, http://doi.wiley.com/10.1029/2012JG002128, 2012.

Reick, C. H., Raddatz, T., Brovkin, V., and Gayler, V.: Representation of natural and anthropogenic land cover change in MPI-ESM, J. Adv. Model. Earth Syst., 5, 459–482, https://doi.org/10.1002/jame.20022, http://doi.wiley.com/10.1002/jame.20022, 2013.

Saatchi, S. S., Harris, N. L., Brown, S., Lefsky, M., Mitchard, E. T. A., Salas, W., Zutta, B. R., Buermann, W., Lewis, S. L., Hagen, S., Petrova, S., White, L., Silman, M., and Morel, A.: Benchmark map of forest carbon stocks in tropical regions across three continents., Proc. Natl. Acad. Sci. U. S. A., 108, 9899–904, https://doi.org/10.1073/pnas.1019576108, http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3116381{&}tool=pmcentrez{&}rendertype=abstract, 2011.

Sankaran, M., Hanan, N. P., Scholes, R. J., Ratnam, J., Augustine, D. J., Cade, B. S., Gignoux, J., Higgins, S. I., Le Roux, X., Ludwig, F., Ardo, J., Banyikwa, F., Bronn, A., Bucini, G., Caylor, K. K., Coughenour, M. B., Diouf, A., Ekaya, W., Feral, C. J., February, E. C., Frost, P. G. H., Hiernaux, P., Hrabar, H., Metzger, K. L., Prins, H. H. T., Ringrose, S., Sea, W., Tews, J., Worden, J., and Zambatis, N.: Determinants of woody cover in African savannas., Nature, 438, 846–849, https://doi.org/10.1038/nature04070, 2005.

Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J. O., Levis, S., Lucht, W., Sykes, M. T., Thonicke, K., and Venevsky, S.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model, Glob. Chang. Biol., 9, 161–185, https://doi.org/10.1046/j.1365-2486.2003.00569.x, http://doi.wiley.com/10.1046/j.1365-2486.2003.00569.x, 2003.

Staver, A. C., Archibald, S., and Levin, S.: Tree cover in sub-Saharan Africa: Rainfall and fire constrain forest and savanna as alternative stable states, Ecology, 92, 1063–1072, https://doi.org/10.1890/10-1684.1, http://www.esajournals.org/doi/10.1890/10-1684.1, 2011a.

Staver, A. C., Archibald, S., and Levin, S. A.: The Global Extent and Determinants of Savanna and Forest as Alternative Biome States, Science (80-.)., 334, 230–232, https://doi.org/10.1126/science.1210465, http://www.sciencemag.org/cgi/doi/10.1126/science.1210465, 2011b.

Stevens, B., Giorgetta, M., Esch, M., Mauritsen, T., Crueger, T., Rast, S., Salzmann, M., Schmidt, H., Bader, J., Block, K., Brokopf, R., Fast, I., Kinne, S., Kornblueh, L., Lohmann, U., Pincus, R., Reichler, T., and Roeckner, E.: Atmospheric component of the MPI-M Earth System Model: ECHAM6, J. Adv. Model. Earth Syst., 5, 146–172, https://doi.org/10.1002/jame.20015, http://doi.wiley.com/10.1002/jame.20015, 2013.

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, 1991–2011, https://doi.org/10.5194/bg-7-1991-2010, http://www.biogeosciences.net/7/1991/2010/, 2010.

Townsend, J., Carroll, M., DiMiceli, C., Sohlberg, R., Hansen, M., and DeFries, R.: Vegetation Continuous Fields MOD44B, 2001-2010 Percent Tree Cover, Collection 5, Version 051, 2011.

Xu, C., Hantson, S., Holmgren, M., van Nes, E. H., Staal, A., and Scheffer, M.: Remotely sensed canopy height reveals three pantropical ecosystem states, Ecology, 97, 2518–2521, https://doi.org/10.1002/ecy.1470, http://doi.wiley.com/10.1002/ecy.1470, 2016.

Yin, Z., Dekker, S. C., van den Hurk, B. J. J. M., and Dijkstra, H. A.: Bimodality of woody cover and biomass across the precipitation gradient in West Africa, Earth Syst. Dyn., 5, 257–270, https://doi.org/10.5194/esd-5-257-2014, http://www.earth-syst-dynam.net/5/257/2014/, 2014.

Yue, C., Ciais, P., Zhu, D., Wang, T., Peng, S. S., and Piao, S. L.: How have past fire disturbances contributed to the current carbon balance of boreal ecosystems?, Biogeosciences, 13, 675–690, https://doi.org/10.5194/bg-13-675-2016, https://www.biogeosciences.net/13/675/2016/, 2016.