

We thank the reviewers for their constructive comments on our manuscript. In the following paragraphs, the reviewers' comments are in black font and our point-by-point responses are in blue.

## General comments

In this manuscript, Seo and Kim present the results of a study designed to assess the relative and interactive effects of simulating fire and dynamic vegetation on carbon and water cycling in the Community Land Model. One especially interesting finding is that fire seems to increase net ecosystem productivity, but only when dynamic vegetation is turned off. Many of the other results are not very novel, but are appropriate for Geoscientific Model Development because they add evidence supporting existing findings, and could help to interpret future CLM experiments.

This work could be valuable for the large community of researchers using CLM, as well as for global vegetation and land system modelers in general. Unfortunately, certain experimental design choices, coupled with uncertain explanation of model run setups, render parts of this manuscript impossible to confidently evaluate. I thus recommend that this paper be resubmitted with major revisions.

## Specific comments

The spinup and transient model runs need to be much better explained. Table 1 would have been a good place to clarify things, but as it is now that table does not really give any useful information. Here's the information I would like to see in a revised Table 1, along with the gaps left by the Methods text (and a read through of the Methods for Qiu and Liu 2016):

	CLM4.5BGC 1850	CLM4.5BGC 20th cent.	BGConly	BGC-DV
Time	???	1901–2000	200 years	200 years
Climate forcings	???	1901–2000 (CRU-NCEP)	Repeated 1991– 2000 (CRU- NCEP)	Repeated 1991– 2000 (CRU- NCEP)
[CO <sub>2</sub> ]	???	???	???	???
Biogeog. shifts?	Yes?	Yes?	No (constant map)	Yes
Initial veg.	No (bare soil)?	Yes (as re- sulting from “CLM4.5BGC 1850”)?	No (bare soil)?	No (bare soil)?
Initial soil	Uninitialized	As resulting from “CLM4.5BGC 1850”	As resulting from “CLM4.5BGC 20th cent.”	As resulting from “CLM4.5BGC 20th cent.”
Land use	???	???	At least crops?	No?
Fire	On?	On?	BGConly-F: On BGConly-NF: Off	BGC-DV-F: On BGC-DV-NF: Off

>> There was a mistake in the original manuscript about the time period of climate forcing. We recycled the forcing of the 1961–2000 CRU-NCEP data, not the 1991–2001 data, for BGConly and BGC runs. This has been corrected in L159 and added to Table 1 in the revised manuscript.

>> As per reviewer's suggestion, we have added the detailed explanation of a series of different experiments in Table 1.

*Table 1: Configurations of experiments used in study.*

	BGC for year 1850	BGC for 20th century	BGConly	BGC-DV
Time	-	1901–2000	200 yr	200 yr
Climate forcing (CRU-NCEP)	Repeated 1901–1920	1901–2000	Repeated for five times	Repeated for five times
[CO <sub>2</sub> ]	1850	1901–2000	2000	2000
Biogeography shifts	No	Yes	No	Yes
Initial vegetation	No	From BGC year 1850	From BGC for 20th century	No
Initial soil	No	From BGC year 1850	From BGC for 20th century	From BGC for 20th century
Land use	17 PFTs for 1850	17 PFTs for 20th century	17 PFTs for 2000	Simulated 15 PFTs (except crops)
Fire	On	On	On (BGConly-F) Off (BGConly-NF)	On (BGC-DV-F) Off (BGC-DV-NF)

It is unclear exactly which runs were initialized with no vegetation (i.e., bare soil) because it is unclear what is being referred to by “In these simulations” on L153. The idea that the BGConly and BGC-DV runs might be initialized with suddenly bare ground is concerning; this choice could have serious carbon cycling implications by itself. This should be justified, and well.

>> While BGConly runs are initialized with vegetation, restarting from the end of the BGC for 20th century transient run, BGC-DV runs are initialized with no vegetation with soil conditions, restarting from the end of the BGC for 20th century transient run. We marked these on Table 1 to avoid confusion. Such a method for BGC-DV is commonly used to quickly stabilize the vegetation state for the year 2000 from the spun-up soil carbon state (e.g., CLM User Guide, Castillo et al. (2012) and Rauscher et al. (2015)). Furthermore, we used the final 30 years of each 200-year simulation to focus on the results after stabilization.

L148: “In BGC-DV runs, the initial land surface state was bare ground while soil conditions were adjusted with a restart file from the transient run (i.e., BGC run for the 20th century in

*Table 1) (Catillo et al., 2012; Raushcher et al., 2015; Qiu and Liu, 2016; Wang et al., 2016). Therefore, the vegetation state is quickly stabilized for 200 years of the BGC-DV runs since the runs restart from the spun-up soil carbon condition (i.e., after decomposition spin-up). Furthermore, the last 30 yr results of the 200 yr runs are analyzed to focus on the equilibrium states of both BGConly and BGC-DV runs.”*

## References

*CLM User Guide,*

<http://www.cesm.ucar.edu/models/ccsm4.0/clm/models/lnd/clm/doc/UsersGuide/x2507.html>

*Castillo, C. K. G., Levis, S., and Thornton, P.: Evaluation of the new CNDV option of the community land model: Effects of dynamic vegetation and interactive nitrogen on CLM4 means and variability, J. Clim., 25(11), 3702–3714, doi.org/10.1175/JCLI-D-11-00372.1, 2012.*

*Rauscher, S. A., Jiang, X., Steiner, A., Williams, A. P., Michael Cai, D., and McDowell, N. G.: Sea surface temperature warming patterns and future vegetation change, J. Clim., 28(20), 7943–7961, doi.org/10.1175/JCLI-D-14-00528.1, 2015.*

If my interpretation is correct about the “Vegetation at beginning” row, how was the vegetation C present in 2000 removed for the start of the BGConly and BGCDV runs? Was it removed from the land system entirely, or was it all killed and left to decompose?

>> As in the response to the previous suggestion, BGConly runs are initialized with vegetation, restarting from the end of the BGC 20th century transient run, and BGC-DV runs are initialized with no vegetation with soil conditions, restarting from the end of the BGC 20th century transient run. We marked these on Table 1 to avoid confusion. Such a method for BGC-DV is commonly used to quickly stabilize the vegetation state for the year 2000 from the spun-up soil carbon state (e.g., CLM User Guide, Castillo et al. (2012) and Rauscher et al. (2015)). Furthermore, we used final 30 years of each 200 yr simulation to focus on the results after stabiliz of the revised manuscript.

L148: “*In BGC-DV runs, the initial land surface state was bare ground while soil conditions were adjusted with a restart file from the transient run (i.e., BGC run for the 20th century in Table 1) (Catillo et al., 2012; Raushcher et al., 2015; Qiu & Liu, 2016; Wang et al., 2016). Therefore, the vegetation state is quickly stabilized for 200 years of the BGC-DV runs because the runs restart from the spun-up soil carbon condition (i.e., after decomposition spin-up). Furthermore, the last 30 yr results of the 200 yr runs are analyzed to focus on the equilibrium states of both BGConly and BGC-DV runs.”*

The use of climate forcings for 1991–2000 seems unwise. Generally, periods of at least 20–30 years are used in this sort of experiment, to better capture the full range of synoptic climate variability. It’s especially egregious to use the 1990s specifically, because the 1998 ENSO event resulted in an extreme fire year.

>> There was a mistake in the original manuscript about the time period of climate forcings.

We recycled the meteorological forcing of 1961–2000 based on the CRU-NCEP data, not 1991–2001 data, for BGConly and BGC runs. This has been corrected in L159 and added to Table 1 in the revised manuscript.

It is only explained near the end of the manuscript (LL 299–300) that crops are not simulated in the BGC-DV experiments. This, along with the “CR” panels in Fig. 3 (although CR is not defined anywhere), leads me to understand that crops are simulated in the BGConly experiments. But nowhere is there any information about (a) other land uses in those experiments, (b) land uses in the spinup and transient experiments, or (c) what is used instead of cropland in the BGC-DV experiments.

>> To clarify why the crop PFTs are not included in BGC-DV runs, we have revised the following paragraph to explain the BGConly and BGC-DV runs in the revised manuscript. Furthermore, Table 1 has been added to clarify the land surface characteristics of different types of runs.

L 93: “*In addition to the SP option, CLM 4.5 can be extended using the biogeochemistry model (BGC) and dynamic vegetation model (DV); CLM simulations with BGC without DV (BGConly) and BGC with DV (BGC-DV) can be configured. BGConly simulates the carbon and nitrogen cycles in addition to biophysics and hydrology in a given distribution of vegetation PFTs (Paudel et al., 2016). In BGConly, phenological variations of LAI are simulated and whole-plant mortality is assumed as an annual mortality rate of 2% without biogeographical changes of the vegetation distribution. In contrast, BGD-DV simulates biogeographical changes in the natural vegetation distribution and mortality as well as seasonal changes of LAI (Castillo et al., 2012; 2013). A PFT can occupy a region or degenerate by competing with other PFTs, or they can coexist under various environmental factors, such as light, soil moisture, temperature, and fire (Zeng, 2010; Song and Zeng, 2013). Plant mortality in BGC-DV is determined by heat stress, fire, and growth efficiency (Rauscher et al., 2015). Note that BGC-DV does not simulate the crop PFTs because it simulates the changes in the natural vegetation only. ”*

>> “CR” in the caption of Figure 3 has been defined in the revised manuscript.

Figure 3: “*Percentages of land cover type (broadleaf evergreen (BE)), needleleaf evergreen (NE), deciduous (DE), shrub (SH), grass (GR), bare ground (BG) and crop (CR)) in BGC-DV-F and BGConly (the same for both BGConly-F and BGConly-NF).*”

Unfortunately, the lack of clarity with regard to the model experiment setups makes confident appraisal of the rest of the manuscript impossible. I will attempt to assess what I can, couching my comments in the necessary uncertainty.

Section 3.1 (comparing simulated burned area with GFED3) is extremely problematic. Although I’m uncertain about the specifics of the experimental design, it seems clear that the

runs are not intended as a way of reflecting reality but rather as an exploration of model mechanics. This is suggested by the use of equilibrium runs using 1991–2000 climate—a period in which the land system was certainly not in equilibrium, because of (among other factors) the continued recovery of forests in the northern hemisphere. Perhaps that's not an issue in these runs: It's possible that land use was turned off (there's no way to know, because it's not described in the Methods), but if that's the case, that's just another reason why a comparison of the model outputs to observations makes little sense. And even if one ignores all that, there's the problem that the simulations use 1991–2000 climate but the comparison is to burned area data from 1999–2011. The 1998 ENSO event resulted in an extreme fire year, which would be captured in the climate forcing (and ideally thus in the model output) but not the observational data. The third paragraph of Sect. 3.3 (LL 213–218) is problematic for the same reasons.

>> There was a mistake in the original manuscript about the time period of climate forcings. We recycled the forcing of 1961–2000 based on CRU-NCEP data, not the 1991–2001 data for BGConly and BGC runs. This has been corrected in L165 and added to Table 1 in the revised manuscript. Thus, we estimated the burned area from BGConly-F and BGC-DV-F runs by averaging the last 30 yr results for 200 yr simulations by repeating the climate forcing for 1961–2000. Therefore, the land systems of both BGConly-F and BGC-DV-F runs are equilibrated. The land use changes are not included as highlighted in Table 1. In summary, we intend to simulate the equilibrium state by repeatedly using the climate forcing.

As pointed out by the reviewer, our runs do not intend to reflect reality, but rather to explore the model process and mechanics. Thus, it is not necessary to validate the burned area against the observations, but it is still valuable to evaluate the model results using the observations.

We have therefore deleted a few unclear sentences and rewritten the paragraph to clarify our intentions and make proper comparisons with the observations. In the revised manuscript, the model results are compared with different versions of GFED datasets (GFED4 and GFED4s as well as GFED3).

L185: “*We also compare the model estimates to the satellite-based observational datasets of GFED (van der Werf et al., 2010; Giglio et al., 2013; van der Werf et al., 2017) (Figure 3). Although the model simulations are not intended to reflect the reality, but rather to understand the model mechanisms under the equilibrium states under the 1961–2000 climate forcing, it is still valuable to assess the model results using the observations. Different versions of GFED datasets provided different sized burned areas: GFED3 (van der Werf et al., 2010), GFED4 (Giglio et al., 2013), and GFED4 with small fires, i.e., GFED4s (van der Werf et al., 2017) suggest the burned area of 371 Mha yr<sup>-1</sup> for 1997–2009, 348 Mha yr<sup>-1</sup> for 1997–2011 and 513 Mha yr<sup>-1</sup> for 1997–2016, respectively. In comparison to the most recent data, i.e., GFED4s, both BGConly-F and BGC-DV-F runs, especially BGC-DV-F, underestimate the burned area in comparison to all three GFED datasets. Possible reasons for this underestimation in BGC-DV-F include the exclusion of agricultural fires and relatively small tree-dominated land*

coverage." The initial model development with a BGC-DV-F type simulation (Li et al., 2012) was carried out in comparison to GFED3 (van der Werf et al., 2010) and BGC-DV-F estimated a burned area ( $320 \text{ Mha yr}^{-1}$ ) similar to that of GFED3 (i.e.,  $371 \text{ Mha yr}^{-1}$ )."

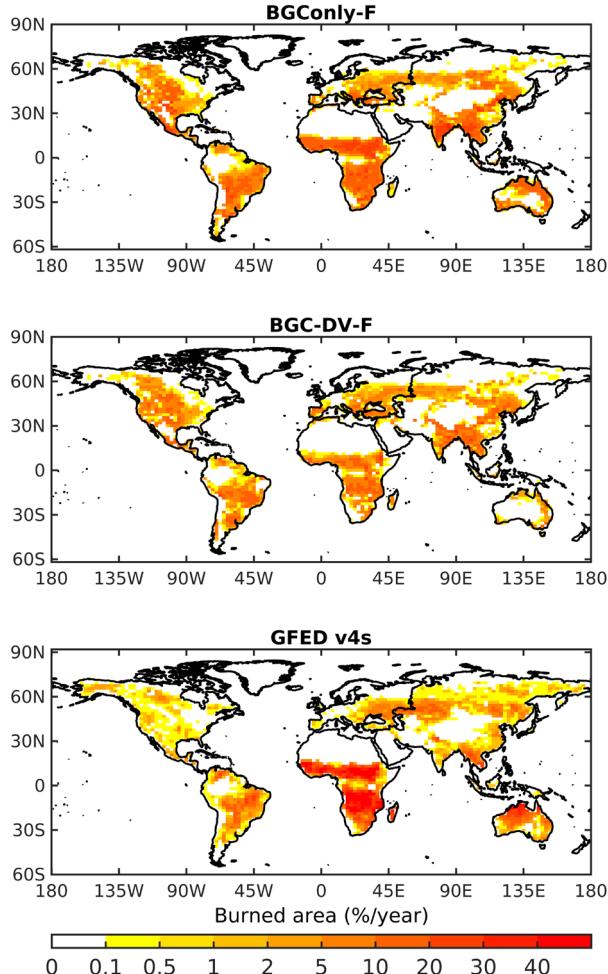


Figure 2: "Annual burned area percentage by grid cell for CLM4.5BGC with fire (BGConly-F), CLM4.5BGCDV with fire (BGC-DV-F), and Global Fire Emission Database version 4 with small fires (GFED4s)".

Figure 3 (land cover comparisons between BGC-DV-F and BGConly) is confounded by the fact that crops were not simulated in the BGC-DV runs. What land cover is being simulated instead? Unless there is some kind of adjustment going on, the area that should be cropland is instead in some other land cover category in BGC-DV-F.

>> As added to Table 1 of the revised manuscript, vegetation in BGC-DV runs consists of 15 different PFTs excluding crops, which can grow over the land according to the environmental conditions, including climate, weather, and soil properties. After the BGC run for the 20th century, cropland is not replaced by any other plants since BGC-DV equilibrium runs for the year 2000 are initialized with bare ground as in L212 of the revised manuscript. As in Figure 3 (percentages of land cover types), grass grows instead of crops in India and needleleaf

evergreen trees replace the agricultural land in the central part of the U.S.

L148: “*In BGC-DV runs, the initial land surface state was bare ground while soil conditions were adjusted with a restart file from the transient run (i.e., BGC run for the 20th century in Table 1) (Catillo et al., 2012; Raushcher et al., 2015; Qiu and Liu, 2016; Wang et al., 2016). Therefore, the vegetation state is quickly stabilized for 200 years of the BGC-DV runs since the runs restart from the spun-up soil carbon condition (i.e., after decomposition spin-up).*”

In Figure 5 and the discussion thereof (LL 184–192), it is unclear what is meant by “changes in the vegetation distribution.” Does that refer to BGC-DV-F vs. BGConlyF, or BGC-DV-F vs. BGC-DV-NF? This makes it unclear how to interpret the results presented in the figure and text: Are we looking at an effect of including dynamic vegetation or of including fire?

>> It is the difference between BGC-DV-F and BGC-DV-NF runs to assess the impact of fires on vegetation distribution. This has been clarified in L216 as well as in Figure 5 of the revised manuscript.

L206: “*Differences in the vegetation distribution between BGC-DV-F and BGC-DV-NF in Figure 5 illustrate a nonlinear change in vegetation distribution in response to post-fire area. The changes are small in areas with minimal fire occurrence or where the burned area fraction is small (0.1–1%).*”

Figure 5: “*Differences in vegetation distribution (bare ground (BG), grass (GR), shrub (SH), deciduous (DE), broadleaf evergreen (BE), and needleleaf evergreen (NE)) ratios between BGC-DV-F and BGC-DV-NF for four burned area categories: under 0.1%, 0.1–1%, 1–10%, and greater than 10%.*”

The following, in Sect. 3.4, is incomplete: “Changes in ET and runoff do not differ markedly between BGConly and BGC-DV, despite differences in the vegetation canopy and height, and soil moisture. This result could be attributed to the fact that an offline CLM was used, which does not allow for land-atmosphere interactions.” It actually also indicates that including dynamic vegetation doesn’t make much difference for the physiological and physical processes of the land system governing evapotranspiration and runoff.

>> As pointed out by the reviewer, we have clarified the implications of small changes in ET and runoff in the revised manuscript as follows.

L288: “*Despite the differences in soil moisture and vegetation canopy and height, changes in ET and runoff do not vary significantly between BGConly and BGC-DV. Thus, including dynamic vegetation does not impact the physiological and physical processes of evapotranspiration and runoff, respectively. However, changes in ET and runoff can be amplified in BGC-DV than in BGConly by modeling the land–atmosphere interactions with a coupled land–atmosphere model (e.g., CLM–CAM) because changes in land characteristics in*

*BGC-DV would feed back to the changes in precipitation. Therefore, the limited impact of fires on precipitation in Li and Lawrence (2017) with the coupled model would be increased by excluding dynamic vegetation in the model.”*

## **Other comments**

The spinup and 20th century runs were performed with CLM4.5BGC, not CLM4.5BGC-DV. What input data were used for land use and vegetation?

>> This has been clarified in Table 1 of the revised manuscript. CLM4.5BGC for the year 1850 is run using the land use data of the year 1850 and CLM4.5BGC for the 20th century is performed using the land use data for the 20th century. In terms of vegetation, BGC for the year 1850 is initialized with bare soils and BGC for the 20th century is initialized using the result of the BGC run for the year 1850.

If changes were to be made to make Sect. 3.1 justifiable (see above), why would GFED3 be used instead of the more recent GFED4, or even better, GFED4s? This could change the interpretations in Sect. 3.1, for instance, since GFED4s gives global burned area of 476 Mha/year—much closer to BGConly-F instead of BGC-DV-F.

>> As per reviewer’s suggestion, we used the GFED4 and GFED4s as well as GFED3 for comparison with our results. We have revised the relevant paragraph and Figure 2 with GFED4s (the most recent version) in the revised manuscript.

L185: “*We also compare the model estimates to the satellite-based observational datasets of GFED (van der Werf et al., 2010; Giglio et al., 2013; van der Werf et al., 2017) (Figure 3). Although the model simulations are not intended to reflect the reality, but rather to understand the model mechanisms under the equilibrium states under the 1961–2000 climate forcing, it is still valuable to assess the model results using the observations. Different versions of GFED datasets provided different sized burned areas: GFED3 (van der Werf et al., 2010), GFED4 (Giglio et al., 2013), and GFED4 with small fires, i.e., GFED4s (van der Werf et al., 2017) suggest the burned area of 371 Mha yr<sup>-1</sup> for 1997–2009, 348 Mha yr<sup>-1</sup> for 1997–2011 and 513 Mha yr<sup>-1</sup> for 1997–2016, respectively. In comparison to the most recent data, i.e., GFED4s, both BGConly-F and BGC-DV-F runs, especially BGC-DV-F, underestimate the burned area in comparison to all three GFED datasets. Possible reasons for this underestimation in BGC-DV-F include the exclusion of agricultural fires and relatively small tree-dominated land coverage.” The initial model development with a BGC-DV-F type simulation (Li et al., 2012) was carried out in comparison to GFED3 (van der Werf et al., 2010) and BGC-DV-F estimated a burned area (320 Mha yr<sup>-1</sup>) similar to that of GFED3 (i.e., 371 Mha yr<sup>-1</sup>).*

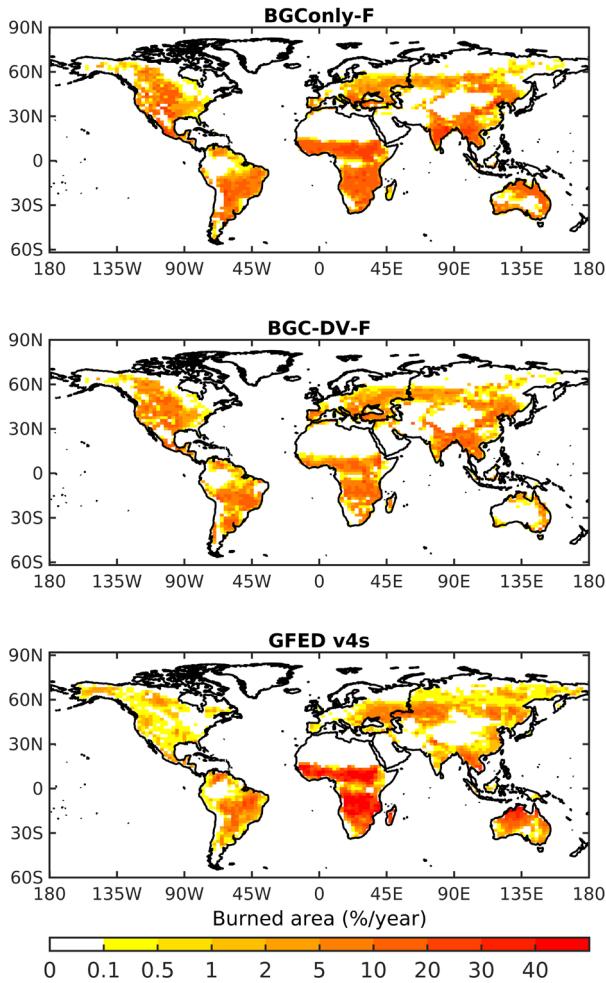


Figure 1: “Annual burned area percentage by grid cell for CLM4.5BGC with fire (BGConly-F), CLM4.5BGCDV with fire (BGC-DV-F), and Global Fire Emission Database version 4 with small fires (GFED4s).”

Tables 3 and 5: It is not clear what the t-tests are actually testing. Are they testing the difference of each experiment’s mean difference from zero (i.e., the effects of including fire), or the difference between the two models’ mean differences (i.e., the interactive effect of including dynamic vegetation and fire)?

>> We performed the t-tests for the difference between the two models’ mean values (BGConly-F vs BGConly-NF and BGC-DV-F vs BGC-DV-NF). The captions of Tables 3, 5, 6 and 7 have been revised accordingly.

Table 3, 5, 6, and 7: “*their differences between the one with fire and the one without fire (i.e., BGConly-F minus BGConly-NF and BGC-DV-F minus BGC-DV-NF)*”

Throughout the paper, more effort should be made to distinguish the discussion of fire effects vs. dynamic vegetation effects.

>> We have revised the manuscript carefully to avoid any confusion with the fire effects and dynamic vegetation effects. In particular, we have clarified the confusing expressions regarding the BGC-DV and BGConly cases in Section 3.3 (Fire impact on carbon balance) and 3.4 (Fire impact on water balance). BGC-DV case means the difference between BGC-DV-F and BGC-DV-NF and BGConly case means the difference between BGConly-F and BGConly-NF. The following paragraphs are examples of these revisions.

L224: “*The impact of fires in BGConly was estimated by calculating the difference between BGConly-F and BGConly-NF, averaged over the final 30 years of each 200 yr simulation. Similarly, the impact of fires in BGC-DV was estimated by calculating the difference between BGC-DV-F and BGC-DV-NF.*”

L 236: “*In addition to direct carbon emissions from fires, fire influences terrestrial carbon sinks by impacting ecosystem processes (Figure 6). Fire increases the NEP in post-fire regions in BGConly simulations (i.e., difference between BGConly-F and BGConly-NF, Figure 6a), which is consistent with the findings of the previous studies (Li et al., 2014).*”

L243: “*Simulations that ignore vegetation dynamics (i.e., the BGConly runs in this study; Li et al., 2014; Yue et al., 2015) show a global fire-induced NEP increase when comparing fire-on and fire-off runs. However, a decrease in fire-induced NEP is apparent in some regions in BGC-DV simulations (i.e., differences between BGC-DV-F and BGC-DV-NF, Figure 6b).*”

L 261: “*The impact of fires on water balance was examined by estimating the changes in runoff, evapotranspiration, and soil moisture between cases with and without fire. The differences between BGConly-F and BGConly-NF were assessed for the case without considering the vegetation dynamics and differences between BGC-DV-F and BGC-DV-F for the case considering the vegetation dynamics (Table 5 and Figure 8).*”

## Technical corrections

L 58: Since the first FireMIP results paper has not been published, it would be more accurate to say “is evaluating” rather than “evaluated”.

>>As per reviewer’s suggestion, we have corrected it.

L58: “*In this respect, the Fire Model Intercomparison Project (FireMIP) evaluates the strength and weakness of each fire model by comparing the performance of different fire models and suggesting improvements for individual models (Rabin et al., 2017).*”

L 64:

- The most recent version of GFED is v4, not v3.
- Because it’s the name of a specific sensor rather than a general technology, Moderate

Resolution Imaging Spectroradiometer should be capitalized.

- In addition to MODIS fire counts, GFED also considers MODIS burned area.

>> We have corrected it as follows.

L63: “*and the satellite-based Global Fire Emission Database version 3 (GFED3), which is derived from Moderate Resolution Imaging Spectroradiometer (MODIS) fire count products and burned areas, has been used to improve fire parameterizations*”

L 81: Period missing after “1.2”.

>> We have corrected it.

L 301–302: “Thresholds used” should be “Thresholds are used”.

>> The phrase of “Thresholds used to estimate fuel combustibility” is a subject in the sentence and thus has not been changed in the revised manuscript.

Fig. 3:

- “Plant cover” should be simply “Coverage” or something similar, because bare ground by definition has no plants.

>> We have used “land coverage” instead of “plant cover”.

- “BGConly” should be “BGConly-F”.

>> The same land cover is used in BGConly-F and BGConly-NF runs from the observations (i.e., MODIS) and thus we used BGConly in the caption of Figure 3

- L 512: “bare ground (BE)” should be “bare ground (BG)”. CR is not defined.

>> The acronym of BG in the figure is corrected and the acronym of CR is clarified in the caption of Figure 3.

Figure 2: “*Percentages of land cover type (broadleaf evergreen (BE)), needleleaf evergreen (NE), deciduous (DE), shrub (SH), grass (GR), bare ground (BG) and crop (CR)) in BGC-DV-F and BGConly (the same for both BGConly-F and BGConly-NF).*”

Fig. 6: “Differene” should be “Difference”.

>> We have corrected it in Figure 6 as follows.

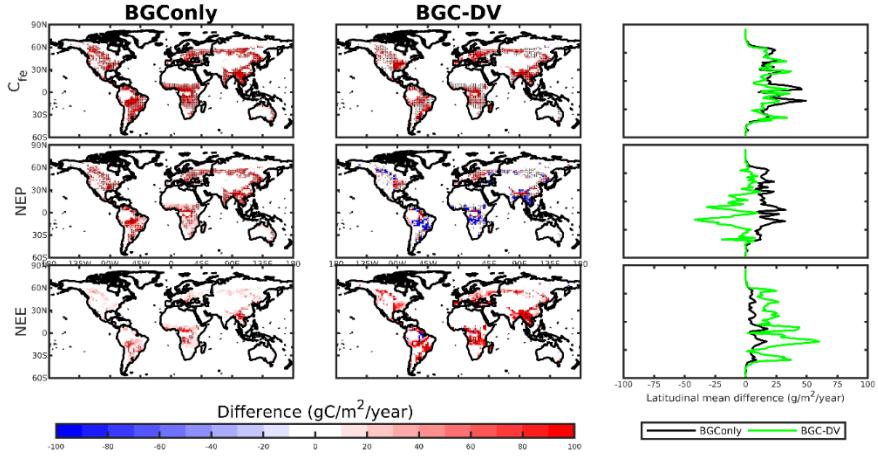


Figure 6: ‘Differences in carbon emissions ( $C_{fe}$ ), net ecosystem production (NEP), and net ecosystem exchange (NEE) due to fires in BGConly (BGConly-F minus BGConly-NF; left column) and BGC-DV (BGC-DV-F minus BGC-DV-NF; middle column). Hashed areas indicate that the difference passed the Student’s t-test at the 0.05 significance level. Latitudinal mean differences are plotted in far-right column.

1   **Interactive impacts of fire and vegetation dynamics on global**  
2   **carbon and water budget using Community Land Model version**  
3   **4.5**

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7   **Abstract**

8   Fire plays an important role in terrestrial ecosystems. The burning of biomass affects carbon and water fluxes and  
9   vegetation distribution. To understand the effect of interactive processes of fire and ecological succession on surface  
10   carbon and water fluxes, this study employed the Community Land Model version 4.5 to conduct a series of  
11   experiments that included and excluded fire and dynamic vegetation processes. Results of the experiments that  
12   excluded the vegetation dynamics showed a global increase in net ecosystem production (NEP) in post-fire regions,  
13   whereas the inclusion of vegetation dynamics revealed a fire-induced decrease in NEP in some regions, which was  
14   depicted when the dominant vegetation type was changed from trees to grass. Carbon emissions from fires are  
15   enhanced by reduction in NEP when vegetation dynamics are considered; however, this effect is somewhat mitigated  
16   by the increase in NEP when vegetation dynamics are not considered. Fire-induced changes in vegetation modify the  
17   soil moisture profile because grasslands are more dominant in post-fire regions. This results in less moisture within  
18   the top soil layer than that in unburned regions, even though transpiration is reduced overall. These findings are  
19   different from those of previous fire model evaluations that ignored vegetation dynamics and thus, highlight the  
20   importance of interactive processes between fires and vegetation dynamics in evaluating recent model developments.

21   **Keywords**

22   Fire model, Dynamic vegetation model, Terrestrial carbon balance, Community Land Model, Terrestrial water balance  
23

24     **1 Introduction**

25     Wildfire is a natural process that influences ecosystems and the global carbon and water cycle (Gorham, 1991;  
26     Bowman et al., 2009; Harrison et al., 2010). Climate and vegetation control the occurrence of fires and their spread,  
27     which in turn affects climate and vegetation (Vilà et al., 2001; Balch et al., 2008). When fire destroys forests and  
28     grasslands, the distribution of vegetation is also affected (Clement and Touffet, 1990; Rull, 1999). Wildfires are major  
29     sources of trace gases and aerosols, which are important elements in the radiative balance of the atmosphere (Scholes  
30     et al., 1996; Fiebig et al., 2003). Aerosols affect surface air temperature, precipitation, and circulation (Tarasova et al.,  
31     1999; Lau and Kim, 2006; Andreae and Rosenfeld, 2008).

32       Changes in soil properties occur in regions affected by fire; leaves and roots can be annihilated in those  
33     regions (Noble et al., 1980; Swezy and Agee, 1991). Each year, fires transport approximately 2.1 Pg of carbon from  
34     soil and vegetation into the atmosphere in the form of carbon dioxide and other carbon compounds (van der Werf et  
35     al., 2010). Harden et al. (2000) report that approximately 10–30% of annual net primary productivity (NPP) disappears  
36     through fires in upland forests. Transpiration and canopy evaporation decrease with the reduction in leaf numbers  
37     (Clinton et al., 2011; Beringer et al., 2015). Soil develops a water-repellent layer during fires due to intense heating  
38     (DeBano, 1991) and ash produced by biomass combustion impacts the quality of runoff (Townsend and Douglas,  
39     2000).

40       In post-fire regions, plant distribution gradually changes over time from bare ground to grassland, shrubland,  
41     and finally to forest during ecological succession (Prach and Pyšek, 2001). Therefore, the structure and distribution  
42     of vegetation can be altered by fires in post-fire regions (Wardle et al., 1997). The existence of grass and trees in the  
43     savanna can be attributed to fires (Hochberg et al., 1994; Sankaran et al., 2004; Baudena et al., 2010). However, fires  
44     can also wipe out succession.

45       Fire affects many aspects of the Earth system. Therefore, a process-based representation of fires is included  
46     in dynamic global vegetation models (DGVMs), land surface models (LSMs), and Earth system models (ESMs; Rabin  
47     et al., 2017). Previous studies reported the incorporation of fire models into global climate models to investigate the  
48     occurrence and spread of fires and how they impact climate and vegetation (e.g., Pechony and Shindell, 2010; Li et  
49     al., 2012; 2013). Bond et al. (2005) used the Sheffield DGVM and performed the first global study on the extent to  
50     which fires determine global vegetation patterns by preventing ecosystems from achieving potential height, biomass,  
51     and dominant functional types expected under ambient conditions (i.e., potential vegetation).

52       In recent years, global fire models have become more complex (Hantson et al., 2016). Different fire models  
53     parameterize different impact factors such as fuel moisture, fuel size, probability of lightning, and human effects. In  
54     this respect, the Fire Model Intercomparison Project (FireMIP) evaluates the strength and weakness of each fire model  
55     by comparing the performance of different fire models and suggesting improvements for individual models (Rabin et  
56     al., 2017).

57       A process-based fire parameterization of intermediate complexity has been developed and assessed within  
58     the framework of the National Center for Atmospheric Research (NCAR) the Community Earth System Model  
59     (CESM) (Li et al. 2012; 2013; 2015). The satellite-based Global Fire Emission Database version 3 (GFED3), which  
60     is derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) fire count products and the burned

61 area, has been used to improve fire parameterization. The impact of fires on carbon, water, and energy balance has  
62 also been investigated within the CESM framework (Li et al., 2014; Li and Lawrence, 2017). However, although these  
63 studies have considered land–atmosphere interactions using the Community Land Model (CLM) coupled with an  
64 atmospheric model, they have ignored the changes in global vegetation patterns caused by fires, even though the initial  
65 model developed by Li et al. (2012) was designed to consider the vegetation dynamics (i.e., changes in vegetation  
66 distribution) within the CLM-DGVM.

67 It is important to understand the individual and combined impacts of fires and vegetation distribution on  
68 water and carbon exchange; however, few studies to date have assessed this complicated global process. Therefore,  
69 in this study, we aim to understand the interactive effects of fires and ecological succession on carbon and water fluxes  
70 on the land surface. Specifically, using the NCAR CLM, we conduct a series of numerical experiments that include  
71 and exclude fire and dynamic vegetation processes. Our results show that the impact of fires on carbon and water  
72 balance (especially in net ecosystem production (NEP) and soil moisture) on ecological succession is different from  
73 that on static vegetation.

## 74 **2 Model and experimental design**

### 75 **2.1 Model description**

76 This study used CLM version 4.5, which is the land model of the NCAR CESM version 1.2. The CESM is  
77 maintained by NCAR’s Climate Global Dynamics Laboratory (CGD) and comprises different components such as  
78 land, atmosphere, ocean, land ice, and ocean ice (Worley et al., 2011; Kay et al., 2012). Each component utilizes  
79 various formulae to represent the complex interplay of physical, chemical, and biological processes and each can be  
80 used either independently or as coupled (Smith et al., 2010; Neale et al., 2012; Bonan et al., 2013). Land surface in  
81 the CLM is represented by sub-grid land cover (glacier, lake, wetland, urban, or vegetated) and vegetation coverage  
82 is represented by 17 plant functional types (PFTs) comprising 11 tree PFTs, 2 crop PFTs, 3 grass PFTs, and bare  
83 ground. For a detailed description of the model, please refer to Lawrence et al. (2011).

84 CLM can be run by including different levels of vegetation processes. In the satellite phenology (SP) option,  
85 vegetation coverage and the state (i.e., leaf area index, LAI) of different PFTs on land surface can be set based on the  
86 satellite-derived climatological data. The coverage of different PFTs is set using climatological data (Lawrence and  
87 Chase, 2007), derived from a variety of satellite products including MODIS and Advanced Very High-Resolution  
88 Radiometer data. Land fractions are divided into bare ground, grass, shrub, and evergreen/deciduous trees. In addition,  
89 grass, shrub, and tree PFTs are classified into tropical, temperate, and boreal types, based on the physiology and  
90 climate rules of Nemani et al. (1996). Vegetation is further divided into C3 or C4 plants based on MODIS-derived  
91 LAI values and the mapping methods of Still et al. (2003). Climatological LAI is set to differ between months but not  
92 between years.

93 In addition to the SP option, CLM 4.5 can be extended using the biogeochemistry model (BGC) and dynamic  
94 vegetation model (DV); CLM simulations with BGC without DV (BGConly) and BGC with DV (BGC-DV) can be  
95 configured. BGConly simulates the carbon and nitrogen cycles in addition to biophysics and hydrology in a given

96 distribution of vegetation PFTs (Paudel et al., 2016). In BGConly, phenological variations of LAI are simulated and  
97 whole-plant mortality is assumed as an annual mortality rate of 2% without biogeographical changes of the vegetation  
98 distribution. In contrast, BGD-DV simulates biogeographical changes in the natural vegetation distribution and  
99 mortality as well as seasonal changes of LAI (Castillo et al., 2012; 2013). A PFT can occupy a region or degenerate  
100 by competing with other PFTs, or they can coexist under various environmental factors, such as light, soil moisture,  
101 temperature, and fire (Zeng, 2010; Song and Zeng, 2013). Plant mortality in BGC-DV is determined by heat stress,  
102 fire, and growth efficiency (Rauscher et al., 2015). Note that BGC-DV does not simulate the crop PFTs because it  
103 simulates the changes in the natural vegetation only.

104 In the fire model (Li et al., 2012, 2013; Bonan et al., 2013), fire types are divided into four groups: non-peat  
105 fires outside cropland and tropical closed forests, agricultural fires, deforestation fires in tropical closed forests, and  
106 peat fires. Fire counts are determined based on natural and artificial ignition, fuel availability, fuel combustibility, and  
107 anthropogenic and unsuppressed natural fires related to socioeconomic conditions. The burned area is calculated by  
108 multiplying the fire count by the average fire spread, which is considered to be driven by wind speed, PFT, fuel  
109 wetness, and socioeconomic factors. In other words, the burning and spread of fire are related to the CLM input  
110 parameters of climate and weather conditions, vegetation conditions, socioeconomic conditions, and population  
111 density. After biomass and peat burning are calculated, trace gas and aerosol emissions as well as carbon emissions,  
112 which are the byproducts of fires, are estimated.

113 Once the burned area is identified, impacts of the fire on vegetation mortality, peat burning, and carbon cycle,  
114 can be addressed. The amount of carbon emitted from the fire ( $E$ ) is calculated as follows:

$$115 \quad E = A \cdot C \cdot CC, \quad (1)$$

116 where  $A$  is the burned area;  $C$  is a vector of elements including carbon density of the leaf stem and the root and transfer  
117 and storage of carbon;  $CC$  is the corresponding combustion completeness factor vector.

118 Burned area also impacts the carbon and nitrogen pools of the vegetation, which are related to leaf, stem, and  
119 root; fire changes the vegetation state (e.g., LAI) and vegetation height during the burning period in both BGConly  
120 and BGC-DV runs. However, the number of individual PFTs does not change in BGConly, but decreases by biomass  
121 burning in BGC-DV. In other words, individual plants are killed by fire only when the DV option is included in the  
122 model. The number of PFTs killed by fire ( $P_{distrub}$ ) is calculated using equation (2).

$$123 \quad P_{distrub} = \frac{A_b}{f A_g} P \xi, \quad (2)$$

124 where  $P$  is the population density for each PFT,  $\xi$  is the whole-plant mortality factor for each PFT,  $A_g$  is the grid cell  
125 area,  $A_b$  is the burned area of each PFT, and  $f$  is the fraction of coverage of each PFT. The whole-plant mortality, the  
126 rate at which plants die completely by fire, is a calibrated PFT-dependent parameter, which is 0.1 for broadleaf  
127 evergreen trees, 0.13 for needleleaf evergreen trees, 0.07 for deciduous trees, 0.15 for shrubs, and 0.2 for grass (Li et  
128 al., 2012).

129 The terrestrial carbon balance is affected when biomass is burned. The net ecosystem exchange (NEE) can  
130 be estimated using NEP (NEP=NPP–heterotrophic respiration (Rh)) and carbon loss due to biomass burning (Cfe).

$$131 \quad NEE = -NEP + C_{fe}. \quad (3)$$

132    **2.2 Experimental design**

133    A series of global numerical experiments were conducted in this study using a spatial resolution of  $1.9^\circ$  longitude  $\times$   
134     $2.5^\circ$  latitude. Global climate data from the Climate Research Unit (CRU)-National Centers for Environmental  
135    Prediction (NCEP) reanalysis were used for atmospheric driving forcing of CLM. Data from 1901 to 2000 included 6  
136    h precipitation, air temperature, wind speed, specific humidity, longwave radiation, and shortwave radiation. Figure 1  
137    summarizes the experimental process used in this study. Initial conditions for the year 1850 equilibrium state were  
138    provided by NCAR and used to simulate the 20th century transient run. The amount of atmospheric carbon dioxide  
139    has increased since the onset of the Industrial Revolution in 1850 and the composition of land cover and vegetation  
140    has changed (Vitousek et al., 1997; Pitman et al., 2004). Therefore, these changes need to be reflected when running  
141    a 20th century transient simulation and the final surface conditions should represent those of the year 2000 after  
142    running the transient simulation using the CLM-BGC model.

143    Using the simulated surface conditions for the year 2000, four different 200 yr equilibrium CLM simulations  
144    (BGConly and BGC-DV simulations with and without the fire model) were conducted (Table 1). For BGConly runs,  
145    a restart file from the transient run was used with and without the fire model (hereafter, BGConly-F and BGConly-  
146    NF, respectively). Similarly, the BGC-DV runs were performed using the same restart file to simulate the equilibrium  
147    vegetation in 200 yr offline BGC-DV runs both with and without the fire model (hereafter, BGC-DV-F and BGC-DV-  
148    NF, respectively; Erfanian et al., 2016). In BGC-DV runs, the initial land surface state was bare ground while soil  
149    conditions were adjusted with a restart file from the transient run (i.e., BGC run for the 20th century in Table 1)  
150    (Catillo et al., 2012; Raushcher et al., 2015; Qiu and Liu, 2016; Wang et al., 2016). Therefore, the vegetation state is  
151    quickly stabilized for 200 years of the BGC-DV runs since the runs restart from the spun-up soil carbon condition (i.e.,  
152    after decomposition spin-up). Furthermore, the last 30 yr results of the 200 yr runs are analyzed to focus on the  
153    equilibrium states of both BGConly and BGC-DV runs. While the fire model is optional when using CLM with BGC,  
154    it is always run when using CLM with BGC-DV. Hence, the model was modified when conducting the BGC-DV-NF  
155    run and the burned area was set to zero to neglect any fire incidences.

156    A comparison between the BGConly-F and BGConly-NF runs enables the isolation of the impact of fire on  
157    land surface, regardless of DV. In addition, the impact of fires and the interactive impacts of fires and vegetation  
158    distribution on the Earth system can be identified by comparing the BGC-DV-F and BGC-DV-NF runs. Note that this  
159    study focuses on the impact of fires and vegetation dynamics on land carbon and water fluxes by forcing the CLM  
160    with the CRU-NCEP climate data (1961–2000) without considering the land–atmosphere feedbacks. Simulations were  
161    run for 200 years from the initial surface conditions of the year 2000 to derive equilibrium land surface conditions. In  
162    addition, the average surface conditions of the last 30 years were compared with the simulation results.

163    **3 Results and discussion**

164    **3.1 Burned area**

165    In this section, we evaluate how the simulated burned areas differ between the runs with and without vegetation  
166    dynamics, i.e., BGC-DV-F and BGConly-F runs. On average, the BGC-DV-F and BGConly-F runs show burned areas

167 of 320 and 487 Mha yr<sup>-1</sup>, respectively. These results are similar to those of previous studies that applied CLM (i.e., Li  
168 et al., 2012; Li and Lawrence, 2017). The fire model of Li et al. (2012) was originally developed by comparing the  
169 BGC-DV-F-type CLM simulations and resulted in 322 Mha yr<sup>-1</sup> for 1997–2004. The BGC-DV-F simulation, under  
170 the equilibrium condition driven by the 1961–2000 CRU-NCEP data in this study, estimates a similar burned area  
171 (320 Mha yr<sup>-1</sup>) to that of Li et al. (2012). Li and Lawrence (2017) estimated the annual burned area as 489 Mha, which  
172 is similar to that of BGConly-F (487 Mha), using a BGC-F type simulation coupled with CAM.

173 In comparison to the burned area of BGConly-F, BGC-DV-F simulates a relatively small burned area because  
174 agricultural fires are excluded in BGC-DV-F and only natural vegetation is simulated (Castillo et al., 2012).  
175 Furthermore, the spatial distribution of burned areas in Figure 2 shows that BGC-DV-F particularly underestimates  
176 the burned area in Africa and Oceania compared to BGConly-F. The differences in vegetation distribution between  
177 BGC-DV-F and BGConly-F in Figure 3, where PFTs, excluding two crop PFTs, are simplified into six vegetation  
178 groups (broadleaf evergreen trees, needleleaf evergreen trees, deciduous trees, shrubs, grasses, and bare ground)  
179 (Rauscher et al., 2015), may impact the size of the burned area. In BGC-DV-F (Figure 3a), evergreen and deciduous  
180 trees show limited growth whereas grass and bare ground are dominant in some regions such as southern Africa.  
181 Overall, BGC-DV-F simulates trees on 37.5% of the global land area while BGConly-F, which is derived from  
182 observations (Figure 3b), indicates that trees cover 41.46% of the global land area (Table 2). More trees provide  
183 increased fuel for the occurrence and spread of fires in BGConly-F than in BGC-DV-F, consistent with the larger  
184 burned area in BGConly-F than in BGC-DV-F.

185 We also compare the model estimates to the satellite-based observational datasets of GFED (van der Werf et  
186 al., 2010; Giglio et al., 2013; van der Werf et al., 2017) (Figure 3). Although the model simulations are not intended  
187 to reflect the reality, but rather to understand the model mechanisms under the equilibrium states under the 1961–2000  
188 climate forcing, it is still valuable to assess the model results using the observations. Different versions of GFED  
189 datasets provided different sized burned areas: GFED3 (van der Werf et al., 2010), GFED4 (Giglio et al., 2013), and  
190 GFED4 with small fires, i.e., GFED4s (van der Werf et al., 2017) suggest the burned area of 371 Mha yr-1 for 1997–  
191 2009, 348 Mha yr-1 for 1997–2011 and 513 Mha yr-1 for 1997–2016, respectively. In comparison to the most recent  
192 data, i.e., GFED4s, both BGConly-F and BGC-DV-F runs, especially BGC-DV-F, underestimate the burned area in  
193 comparison to all three GFED datasets. Possible reasons for this underestimation in BGC-DV-F include the exclusion  
194 of agricultural fires and relatively small tree-dominated land coverage.” The initial model development with a BGC-  
195 DV-F type simulation (Li et al., 2012) was carried out in comparison to GFED3 (van der Werf et al., 2010) and BGC-  
196 DV-F estimated a burned area (320 Mha yr-1) similar to that of GFED3 (i.e., 371 Mha yr-1).

### 197 **3.2 Interactions between vegetation and fire processes**

198 The impact of fires on vegetation distribution is assessed by comparing BGC-DV-F and BGC-DV-NF simulations  
199 (Table 2 and Figures 4 and 5). Figure 4 shows the vegetation distribution of BGC-DV-NF (Figure 4a) and BGC-DV-  
200 F minus BGC-DV-NF (Figure 4b: Figure 4a minus Figure 3a). The plots clearly indicate large differences in vegetation  
201 cover in areas of high fire frequency (i.e., South Africa, South America, western North America, India, and a portion

202 of China) (Table 2), whereas areas with relatively low fire occurrence (i.e., the Arctic and desert regions) show small  
203 differences.

204 We estimated the fraction of burned areas, where fractions are grouped into four categories ( $>10\%$ ,  $10\text{--}1\%$ ,  
205  $1\text{--}0.1\%$  and,  $<0.1\%$ ) for each vegetation type, and investigated the relationship between vegetation distribution and  
206 fire occurrence. Differences in the vegetation distribution between BGC-DV-F and BGC-DV-NF in Figure 5 illustrate  
207 a nonlinear change in vegetation distribution in response to post-fire area. The changes are small in areas with minimal  
208 fire occurrence or where the burned area fraction is small (0.1–1%). However, relatively large changes in vegetation  
209 distribution occur when the burned area fraction exceeds 1%. Furthermore, there are large changes in the vegetation  
210 distribution in areas with burned area fractions above 10%, including increases in bare ground, grass, and shrubs  
211 (31.19, 52.28, and 7.91%, respectively) but decreases in deciduous, needleleaf evergreen, and broadleaf evergreen  
212 trees (8.85, 79.22, and 91.17%, respectively).

213 In ecosystems, plants die in regions where fires occur and grass with rapid growth rates occupies those  
214 regions. Therefore, fire increases the ratio of bare ground and grassland but reduces the number of trees. However,  
215 there are no significant changes in the global fraction of shrubs and deciduous trees in the middle of the ecological  
216 succession process with respect to the presence or absence of fires (Table 2). When a fire occurs in a region where  
217 shrubs grow, the ratio of shrubland is diminished (e.g., in the middle of North America in Figure 4b), but fire increases  
218 the ratio of shrubland in regions where trees grow (e.g., in the southwestern Asia in Figure 4b). Similarly, the number  
219 of deciduous trees increases or decreases due to fires. Thus, the role of fires in areas of shrubland and deciduous trees  
220 varies with the region and the actual vegetation distribution is a result of many factors including fire, climate,  
221 topography, and soil conditions (He et al., 2007; Cimalová and Lososová, 2009).

### 222 **3.3 Fire impact on carbon balance**

223 The direct and indirect impacts of fires on carbon balance were investigated for static and dynamic vegetation cover  
224 (Figure 6 and Table 3). The impact of fires in BGConly was estimated by calculating the difference between BGConly-  
225 F and BGConly-NF, averaged over the final 30 years of each 200 yr simulation. Similarly, the impact of fires in BGC-  
226 DV was estimated by calculating the difference between BGC-DV-F and BGC-DV-NF.

227 Carbon emissions from fires (direct impacts) are shown in Figure 6. The spatial distribution of the BGConly  
228 and BGC-DV runs is similar, but average annual emissions are higher in BGConly (3.5 Pg) than in BGC-DV (3.0 Pg)  
229 because trees are less dominant in BGC-DV than in BGConly, which causes a reduced fuel load.

230 Carbon emission estimates from both BGConly and BGC-DV simulations are relatively high; however, they  
231 do fall within the range of previous findings. For example, 1997–2014 GFED4s data estimated annual direct carbon  
232 emissions as 2.3 Pg. Mouillot et al. (2006) estimated annual carbon emissions as 3.0 Pg for the end of the 20th century  
233 and the 20th century average as 2.5 Pg. Li et al. (2012) estimated the 20th century emissions as 3.5 Pg C yr<sup>-1</sup> using the  
234 CLM3-DGVM and Li et al. (2014) and Yue et al. (2015) both estimated the 20th century emissions as 1.9 Pg C yr<sup>-1</sup>  
235 using the CLM4.5 and ORCHIDE land surface models, respectively.

236 In addition to direct carbon emissions from fires, fire influences terrestrial carbon sinks by impacting  
237 ecosystem processes (Figure 6). Fire increases the NEP in post-fire regions in BGConly simulations (i.e., difference

238 between BGConly-F and BGConly-NF, Figure 6a), which is consistent with the findings of the previous studies (Li  
239 et al., 2014). The overall NEP increase is  $2.5 \text{ Pg C yr}^{-1}$  in this study, which is greater than the value of  $1.9 \text{ Pg C yr}^{-1}$   
240 calculated by Li et al. (2014). However, Li et al. (2014) performed a transient simulation from 1850 to 2004, whereas  
241 the BGConly runs in our study were conducted following an equilibrium simulation using the year 2000 as the  
242 reference year, which means that no fire exchanges are caused by land cover changes.

243 Simulations that ignore vegetation dynamics (i.e., the BGConly runs in this study; Li et al., 2014; Yue et al.,  
244 2015) show a global fire-induced NEP increase when comparing fire-on and fire-off runs. However, a decrease in fire-  
245 induced NEP is apparent in some regions in BGC-DV simulations (i.e., differences between BGC-DV-F and BGC-  
246 DV-NF, Figure 6b). This carbon sink reduction occurs in regions where dominant PFTs change from broadleaf and  
247 needleleaf evergreen trees to grass (Table 3 and Figure 6). Table 4 shows the correlation coefficients between percent  
248 changes in vegetation types and changes in carbon fluxes (NEP, NPP, and  $R_h$ ) for six different PFTs in each grid cell  
249 and Figure 7 shows the broadleaf evergreen tree, needleleaf evergreen tree, and grass PFTs. NEP changes are strongly  
250 linked to changes in dominant PFTs; for example, decreases in broadleaf evergreen and needleleaf evergreen trees  
251 and increases in grass. Furthermore, the changes in NEP and PFTs are related to the changes in NPP and  $R_h$  to some  
252 extent. Our results differ from those of previous studies that did not consider vegetation dynamics (e.g., Amiro et al.,  
253 2010) because the inclusion of vegetation dynamics enables the model to capture NEP decreases in post-fire regions  
254 at the beginning of the post fire-succession.

255 Since land use changes are not considered in this study, the overall impact of fires was estimated by the sum  
256 of direct carbon emissions from fires and terrestrial carbon sinks, i.e., NEP (Eq. 3). Both simulations resulted in net  
257 carbon sources in the post-fire regions, even though different processes were involved. Direct carbon emissions from  
258 fires ( $C_{fe}$  in Eq. 3) were partly negated by the increased NEP in the BGConly runs, but they were enhanced by the  
259 reduction of NEP in BGC-DV runs.

### 260 **3.4 Fire impact on water balance**

261 The impact of fires on water balance was examined by estimating the changes in runoff, evapotranspiration, and soil  
262 moisture between cases with and without fire. The differences between BGConly-F and BGConly-NF were assessed  
263 for the case without considering the vegetation dynamics and differences between BGC-DV-F and BGC-DV-F for the  
264 case considering the vegetation dynamics (Table 5 and Figure 8). Increases in runoff and decreases in  
265 evapotranspiration (ET) were observed in post-fire regions to a different degree, which is consistent with the results  
266 of the previous studies (Neary et al., 2005; Li and Lawrence, 2017). Our study used CLM as a standalone model  
267 without coupling it with atmospheric or ice models, whereas Li and Lawrence (2017) examined the impact of fires on  
268 global water budget using CLM-BGC coupled with the CAM and CICE models and showed that the impact of fires  
269 on global annual precipitation was limited.

270 Li and Lawrence (2017) demonstrated that a reduction in vegetation canopy (LAI; Table 6) is a critical  
271 pathway for fires that decrease ET. Fire events lower the leaf area, which decreases vegetation transpiration and  
272 canopy evaporation; however, they also expose more of the soil to the air and sunlight, which increases soil  
273 evaporation. Post-fire decreases in vegetation height (Table 6) can increase and decrease ET because the resulting

274 decrease in land surface roughness potentially reduces water and energy exchange and leads to higher leaf  
275 temperatures and wind speeds. In this study, both BGConly and BGC-DV runs show that the vegetation canopy is the  
276 main pathway leading to a decrease in ET, which is similar to the findings of Li and Lawrence (2017). In addition, an  
277 examination of the changes in the vegetation composition in post-fire regions shows that the overall impact of those  
278 changes in ET and runoff does not differ greatly when dynamic vegetation is employed in the model.

279 The results show that fire-induced vegetation changes (from trees to grass or bare ground) in BGC-DV lead  
280 to a significant decrease in canopy transpiration and increase in soil evaporation relative to BGConly runs. Fire  
281 destroys plant roots and leaves; changes in the dominant vegetation types in BGC-DV lead to changes in the soil  
282 moisture profile through reduced transpiration (Figure 9 and Table 7). Consequently, there is less water stress in each  
283 soil layer in the burned areas than in unburned areas. Grasslands dominate the post-fire regions in BGC-DV runs and  
284 they absorb and transpire more water from the top soil layer than trees (Mazzacavallo and Kulmatiski, 2015).  
285 Therefore, there is less moisture in the top soil layers in fire affected regions than in unburned regions, although the  
286 overall transpiration is diminished. In summary, fire has an impact on vegetation distribution, which in turn impacts  
287 the soil water profile.

288 Despite the differences in soil moisture and vegetation canopy and height, changes in ET and runoff do not  
289 vary significantly between BGConly and BGC-DV. Thus, including dynamic vegetation does not impact the  
290 physiological and physical processes of evapotranspiration and runoff, respectively. However, changes in ET and  
291 runoff can be amplified in BGC-DV than in BGConly by modeling the land-atmosphere interactions with a coupled  
292 land-atmosphere model (e.g., CLM-CAM) because changes in land characteristics in BGC-DV would feed back to  
293 the changes in precipitation. Therefore, the limited impact of fires on precipitation in Li and Lawrence (2017) with  
294 the coupled model would be increased by excluding dynamic vegetation in the model.

## 295 **4 Conclusions**

296 To understand the interplay between the vegetation dynamics and the impact of fires, we conducted a series of  
297 numerical experiments using CLM with and without fires and dynamic vegetation. In particular, we investigated the  
298 impact of fires on vegetation distribution and how these changes influence terrestrial carbon and water fluxes.

299 The results show that fire interrupts the process of ecological succession, which impacts the global vegetation  
300 distribution. Fire transforms some regions into bare ground and grassland starts to quickly dominate those landscapes  
301 because grass grows faster than trees. For shrubs and deciduous trees in the mid-stages of ecological succession, there  
302 were no large differences in the overall coverage ratios between simulations that included vegetation dynamics and  
303 those that did not. Simulations that did not consider vegetation dynamics showed a fire-induced global increase in  
304 NEP; however, a fire-induced decrease in NEP was detected in some regions in BGC-DV runs. A carbon sink  
305 reduction was also detected in regions where the dominant PFT changed from broadleaf and needleleaf evergreen  
306 trees to grass. While carbon emissions from fires were partly negated by increased terrestrial carbon sinks (NEP) in  
307 BGConly runs, they were enhanced by the reduction of terrestrial carbon sinks in BGC-DV runs when dynamic  
308 vegetation was considered.

309        Fire-induced changes in vegetation from trees to grass or bare ground resulted in a decrease in canopy  
310 transpiration and increased soil evaporation in post-fire regions in BGC-DV runs; however, there were no significant  
311 differences in the overall impact on ET and runoff between the simulations that used dynamic vegetation and those  
312 that did not. However, changes in dominant vegetation types in BGC-DV led to changes in the soil moisture profile.  
313 Furthermore, the increased distribution of grassland cover was more dominant in post-fire regions, which then resulted  
314 in less moisture in the top soil layers than in unburned areas, although transpiration diminished overall.

315        Enabling the vegetation dynamics module in the CLM improves the understanding of the interactive impacts  
316 of fires and vegetation dynamics. However, uncertainty still exists because of the limitations in the simulations of  
317 equilibrium vegetation distribution using CLM with BGC-DV-F; the final equilibrium vegetation state of the BGC-  
318 DV model did not always correspond to the observed distribution (Figure 3). For example, shrubs in the tundra were  
319 rare in both BGC-DV-F and BGC-DV-NF runs. Furthermore, crops, needleleaf evergreen boreal, and shrub boreal  
320 cannot be simulated by the DV module, as also reported in previous studies (Zeng et al., 2008).

321        The fire module in CLM is parameterized to estimate the occurrence, spread, and impacts of fires. Thresholds  
322 used to estimate fuel combustibility depend on relative humidity and surface air temperature; however, these values  
323 may not be suitable for all regions (Zhang et al., 2016). In addition, the economic impact of fire occurrence and the  
324 socioeconomic impact of fire spread are estimated using the input datasets of population density (person km<sup>-2</sup>) and  
325 GDP (US\$ per capita), respectively (Li et al., 2013). Uncertainty due to socioeconomic factors should be noted for  
326 both historical and future simulations because changes in these factors may vary by country (Steelman and Burke,  
327 2006). It is evident that our understanding of fires needs to improve because fires play an important role in the  
328 distribution of vegetation and in carbon, water, and energy cycles. This study shows that fire models are strongly  
329 impacted by vegetation distribution; therefore, fire simulations would improve with the advancement of dynamic  
330 vegetation models.

### 331        **Code and Data Availability**

332        The code of and input datasets for CLM were downloaded from the NCAR CLM website (refer to cesm.ucar.edu).

### 333        **Author Contributions**

334        YK and HS designed the study and HS performed the model simulations by processing the data and modifying the  
335 code. Both YK and HS analyzed the results and wrote the manuscript.

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340

341 **Conflict of Interest**

342 The authors declare that they have no conflicts of interest.

343 **References**

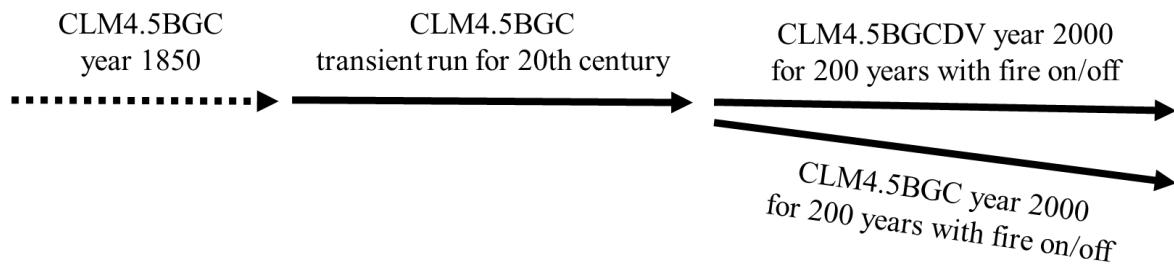
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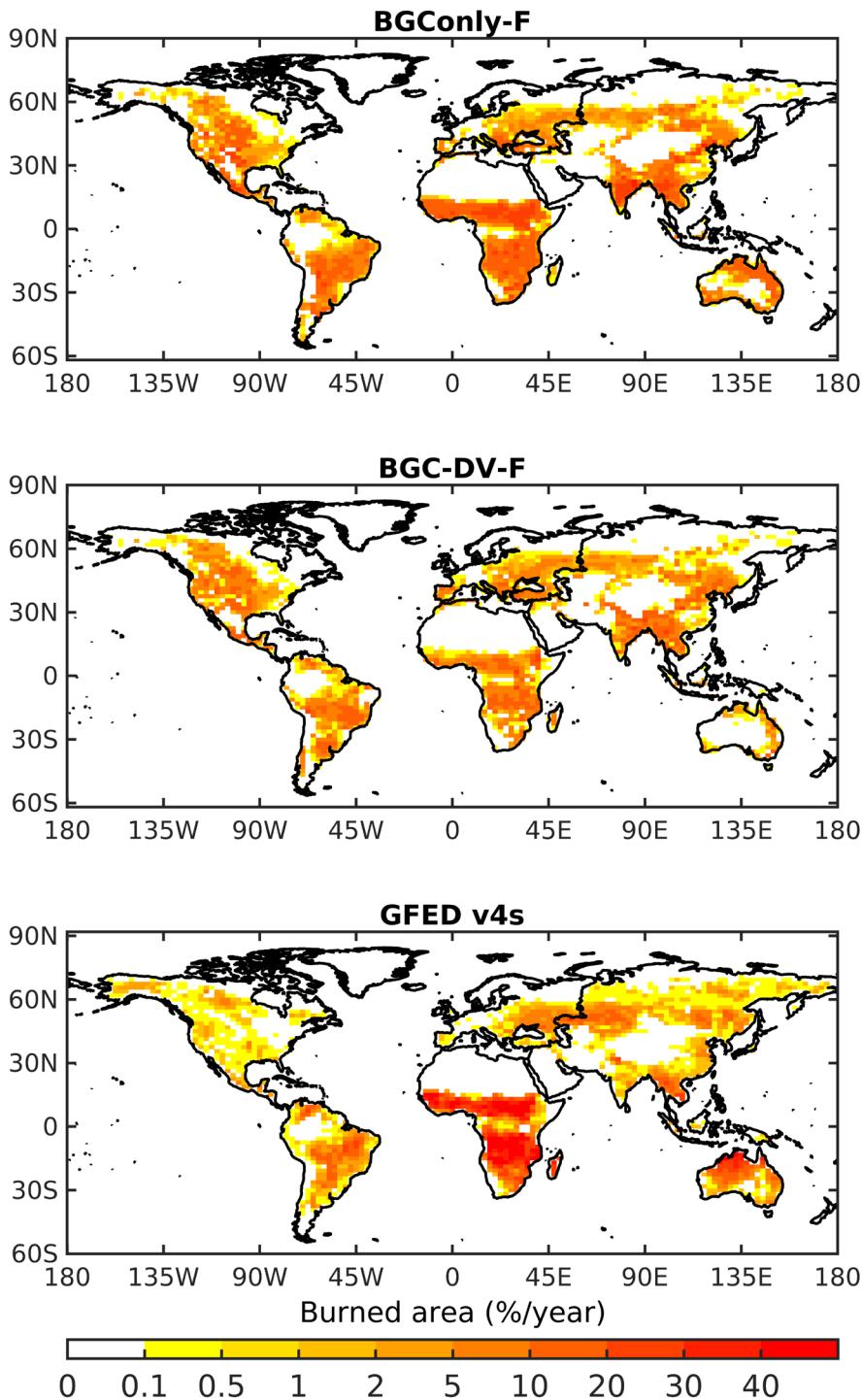
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522 **Figure 1:** Flowchart showing model simulations conducted to investigate the interactive impact of fires and ecological  
523 succession on the Earth system using Community Land Model (CLM4.5) simulations extended with biogeochemistry  
524 (CLM4.5BGC) and BGC with dynamic vegetation (CLM4.5BGCDV).

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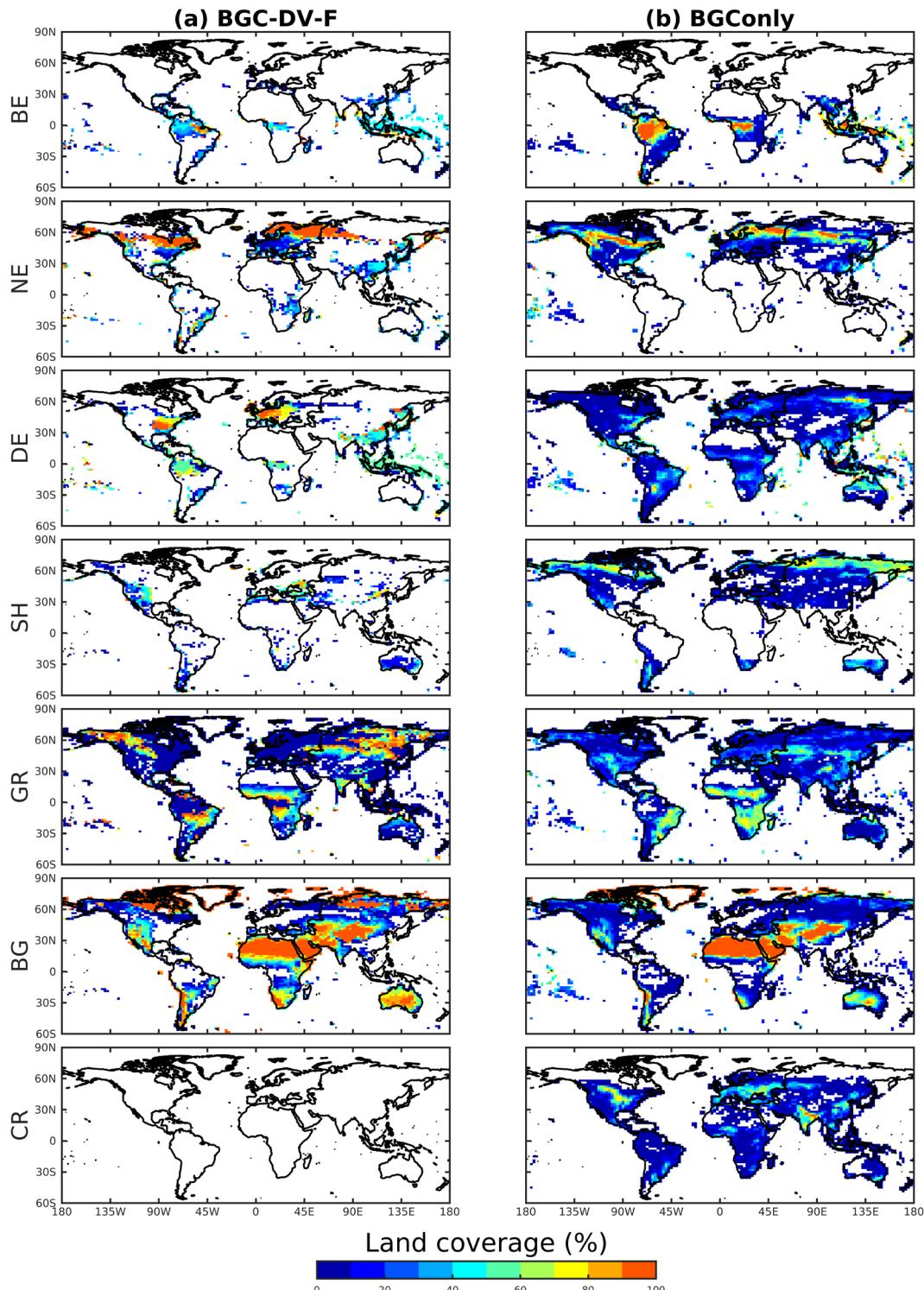


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529 **Figure 2:** Annual burned area percentage by grid cell for CLM4.5BGC with fire (BGConly-F), CLM4.5BGCDV with fire  
530 (BGC-DV-F), and Global Fire Emission Database version 4 with small fires (GFED4s)

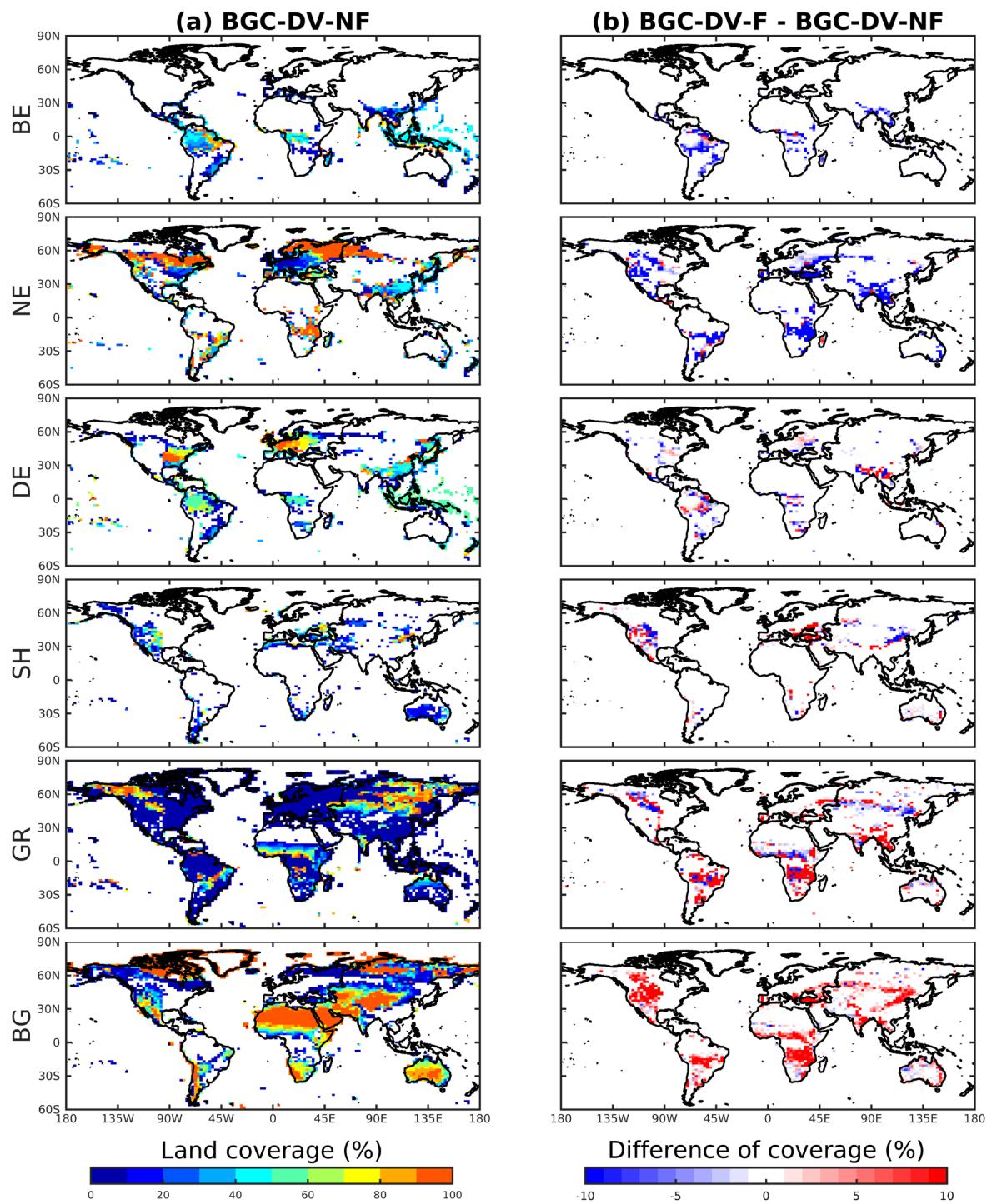
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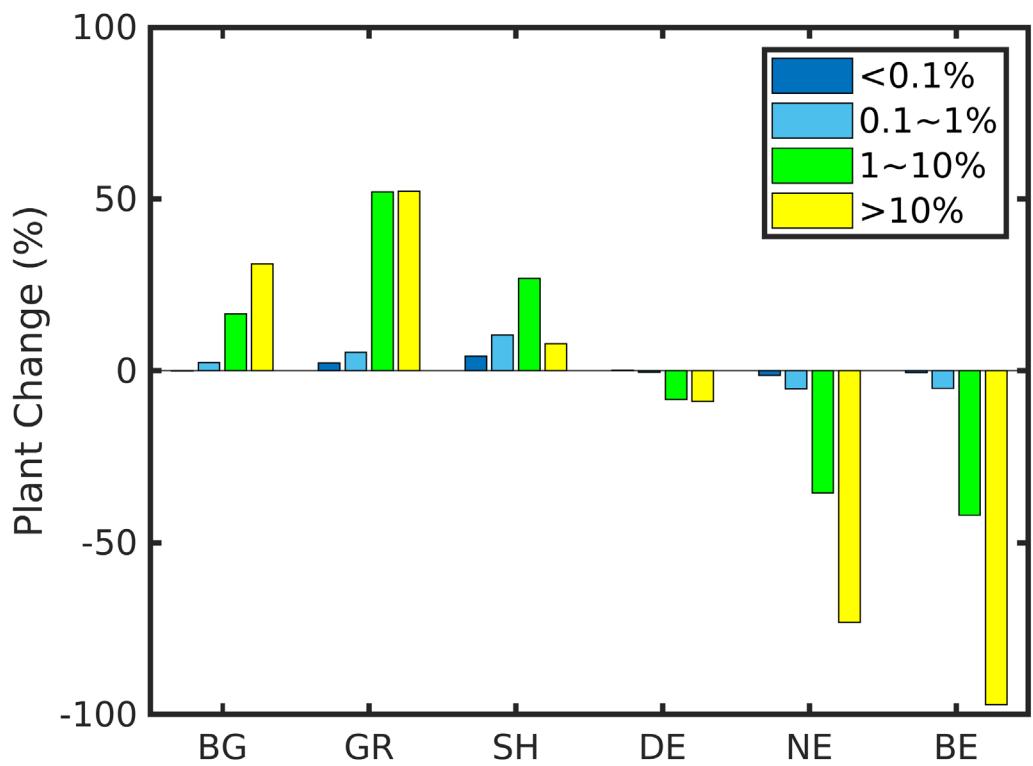
**Figure 3: Percentages of land cover type (broadleaf evergreen (BE)), needleleaf evergreen (NE), deciduous (DE), shrub (SH), grass (GR), bare ground (BG) and crop (CR)) in BGC-DV-F and BGConly (the same for both BGConly-F and BGConly-NF).**



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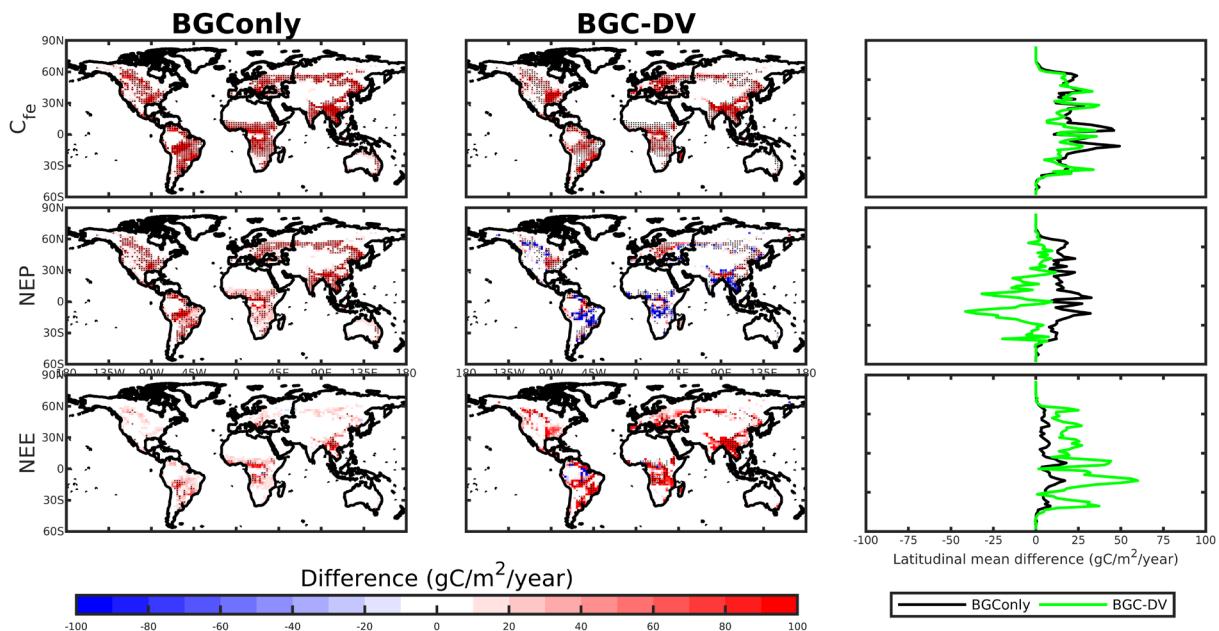
Figure 4: Percentages of land cover (broadleaf evergreen (BE), needleleaf evergreen (NE), deciduous (DE), shrub (SH), grass (GR), and bare ground (BG)) in BGC-DV-NF and differences in plant cover between BGC-DV-F and BGC-DV-NF.



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**Figure 5:** Differences in vegetation distribution (bare ground (BG), grass (GR), shrub (SH), deciduous (DE), broadleaf evergreen (BE), and needleleaf evergreen (NE)) ratios between BGC-DV-F and BGC-DV-NF for four burned area categories: under 0.1%, 0.1~1%, 1~10%, and greater than 10%.

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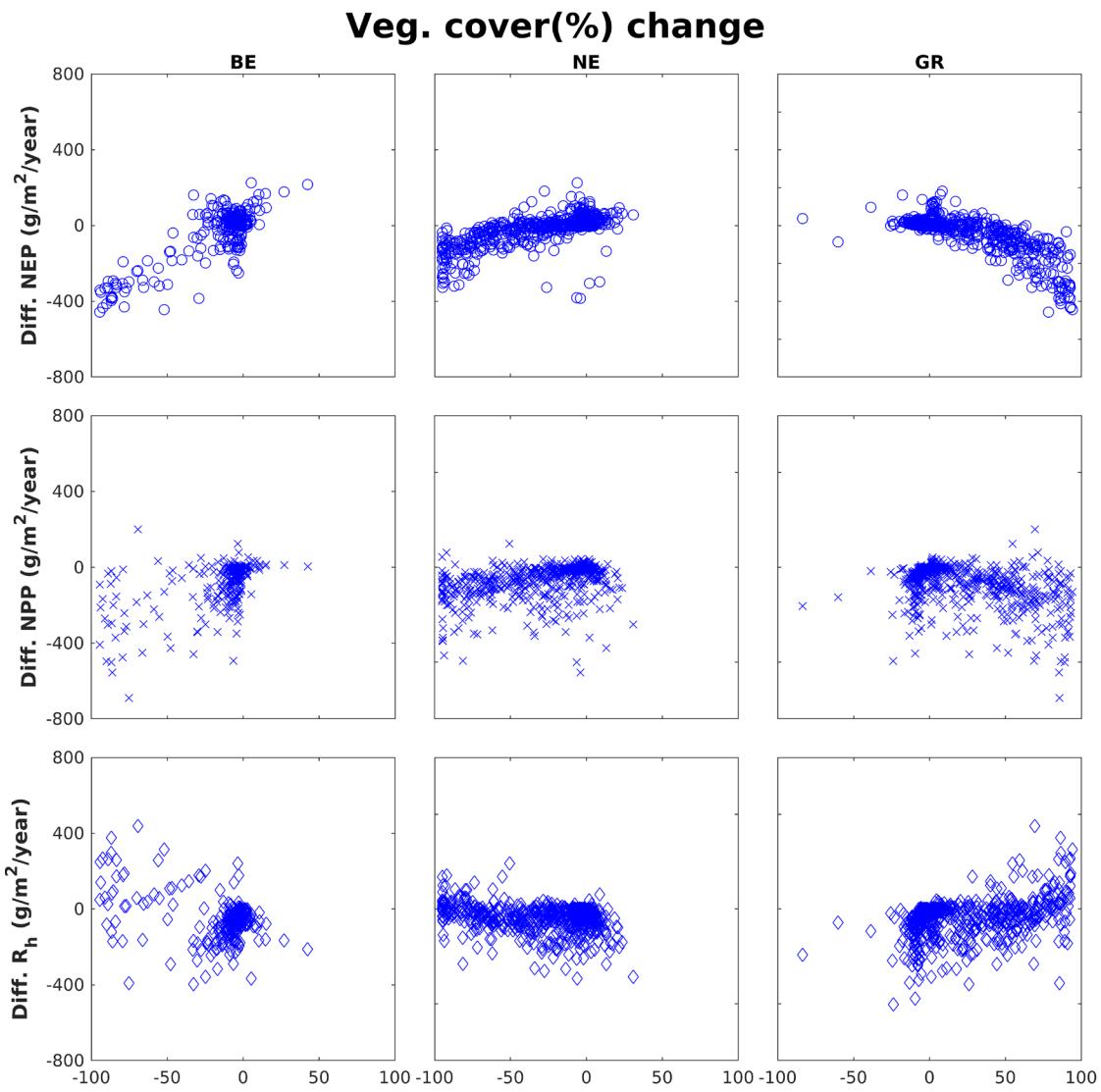


544

545 **Figure 6:** Differences in carbon emissions ( $C_{fe}$ ), net ecosystem production (NEP)  
 546 and net ecosystem exchange (NEE) caused  
 547 by fires in BGConly (BGConly-F minus BGConly-NF; left column) and BGC-DV (BGC-DV-F minus BGC-DV-NF; middle  
 548 column). Hashed areas indicate that the difference passed the Student's t-test at the 0.05 significance level. Latitudinal mean  
 differences are plotted in the far-right column.

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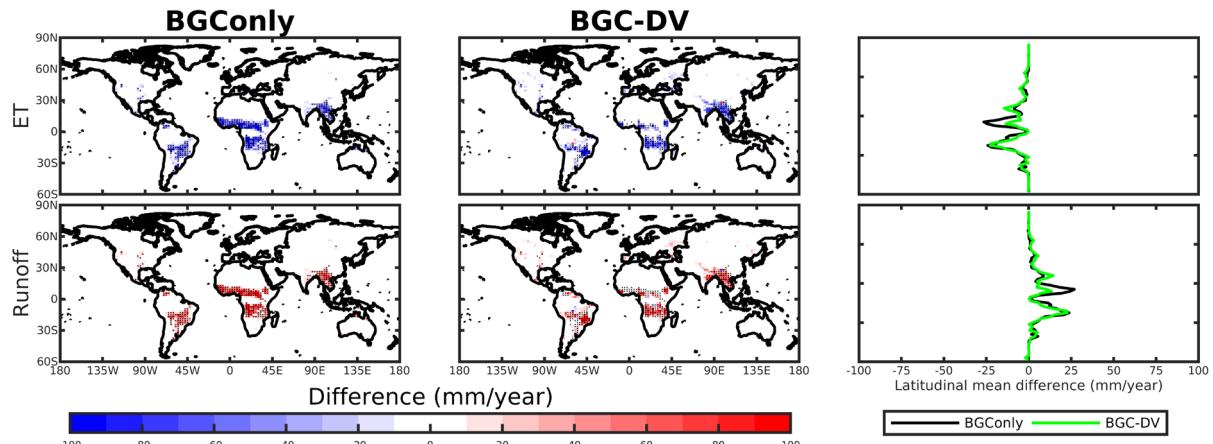
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552 **Figure 7: Differences in net ecosystem production (NEP), net primary productivity (NPP), and heterotrophic respiration**  
 553 **(Rh)) due to fires in BGC-DV (i.e., BGC-DV-F minus BGC-DV-NF) according to percent changes in broadleaf evergreen**  
 554 **and grass (GR) vegetation types.**

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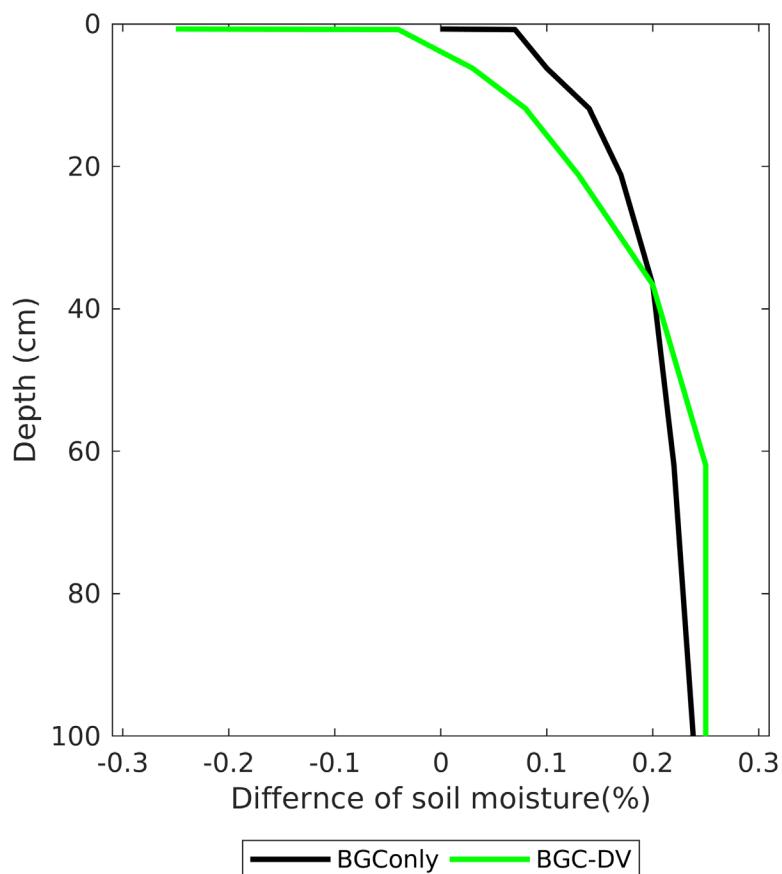
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557 **Figure 8: Differences in evapotranspiration (ET) and runoff due to fire in BGConly (BGConly-F minus BGConly-NF; left**

558 columns) and BGC-DV (BGC-DV-F minus BGC-DV-NF; middle column). Hashed areas indicate that the difference passed

559 the Student's t-test at the 0.05 significance level. Latitudinal mean differences are plotted in the far-right column.

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561

562 **Figure 9: Difference in soil moisture (%) due to fire in BGConly (i.e., BGConly-F minus BGConly-NF) and BGC-DV (i.e.,**

563 BGC-DV-F minus BGC-DV-NF).

564

**Table 1: Configurations of the experiments used in the study**

		BGC for the year 1850	BGC for the 20th century	BGConly	BGC-DV
Time		-	1901–2000	200 yr	200 yr
Climate forcing	Repeated 1901–1920 (CRU-NCEP)		1901–2000 (CRU-NCEP)	Repeated 1961– 2000 for five times (CRU-NCEP)	Repeated 1961– 2000 for five times (CRU-NCEP)
[CO <sub>2</sub> ]	[1850]		[1901–2000]	[2000]	[2000]
Biogeography shifts	No		Yes	No	Yes
Initial vegetation	No		From BGC year 1850	From BGC for 20th century	No
Initial soil	No		From BGC year 1850	From BGC for 20th century	From BGC for 20th century
Land use	17 PFTs for 1850		17 PFTs for 20th century	17 PFTs for 2000	Simulated 15 PFTs (except crops)
Fire	On		On	On (BGConly-F) Off (BGConly-NF)	On (BGC-DV-F) Off (BGC-DV-NF)

567      **Table 2: Percentage (%) land cover types (bare ground, grass, shrub, deciduous, needleleaf evergreen, and broadleaf**  
568      **evergreen) in BGConly, BGC-DV-F, and BGC-DV-NF.**

	BGConly	BGC-DV-F	BGC-DV-NF
Bare ground	28.17	41.21	38.66
Grass	20.13	21.25	16.53
Shrub	8.41	4.75	4.24
Deciduous	12.78	12.29	12.67
Needleleaf evergreen	9.96	14.73	20.54
Broadleaf evergreen	10.31	5.73	7.33
Crop	10.25	-	-

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571      **Table 3: Annual means of carbon budget for GPP, NPP, Ra, R<sub>h</sub>, NEP, NEE, and C<sub>fe</sub> and their differences between one with**  
 572      **fire and one without fire (i.e., BGConly-F minus BGConly-NF, and BGC-DV-F minus BGC-DV-NF) in Pg C yr<sup>-1</sup>. Asterisk**  
 573      **(\*) index indicates that the difference passed the Student's t test at the  $\alpha = 0.05$  significance level.**

	BGConly			BGC-DV		
	BGConly-F	BGConly-NF	Difference	BGC-DV-F	BGC-DV-NF	Difference
C <sub>fe</sub>	3.49	0.00	3.49*	2.98	0	2.98*
GPP	130.51	144.24	-13.73*	122.01	136.93	-14.92*
NPP	56.66	63.17	-6.51*	52.14	55.56	-3.42*
R <sub>a</sub>	73.85	81.08	-7.23*	69.87	81.37	-11.50*
R <sub>h</sub>	52.75	61.73	-8.98*	41.19	43.79	-2.60*
NEP	3.91	1.44	2.47*	13.65	14.67	-1.02*
NEE	-0.42	-1.44	1.02*	-5.27	-8.87	3.60*

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**Table 4: Pearson correlation coefficients between carbon fluxes (NEP, NPP, R<sub>h</sub>) and percentage changes in vegetation cover for broadleaf evergreen (BE), needleleaf evergreen (NE), deciduous (DE), shrub (SH), grass (GR), and bare ground (BG).**

	BE	NE	DE	SH	GR	BG
NEP	0.84	0.68	0.34	-0.28	-0.80	-0.14
NPP	0.56	0.44	0.34	-0.30	-0.47	-0.35
R <sub>h</sub>	-0.36	-0.17	-0.01	-0.13	0.27	-0.30

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580      **Table 5: Annual mean water budgets for ground evaporation (GE), canopy evaporation (CE), canopy transpiration (CE),**  
 581      **evapotranspiration (ET), and total runoff (RO) and the difference between the one with fire and the one without fire (i.e.,**  
 582      **BGConly-F minus BGConly-NF, and BGC-DV-F minus BGC-DV-NF) in  $10^3 \text{ km}^3 \text{ yr}^{-1}$ . Asterisk (\*) index indicates that the**  
 583      **difference passed the Student's t test at the  $\alpha = 0.05$  significance level.**

	BGConly			BGC-DV		
	BGConly-F	BGConly-NF	Difference	BGC-DV-F	BGC-DV-NF	Difference
GE	20.87	19.27	1.60*	23.29	19.61	3.68*
CE	15.71	16.39	-0.68*	15.62	16.88	-1.26*
CT	38.41	40.42	-2.01*	37.68	40.99	-3.31*
ET	74.99	76.08	-1.09*	76.59	77.48	-0.89*
RO	31.09	30.02	1.07*	29.51	28.64	0.87*

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586      **Table 6 Annual mean values for LAI ( $\text{m}^2 \text{ m}^{-2}$ ) and vegetation height (m) and the difference between the one with fire and**  
 587      **the one without fire (i.e., BGConly-F minus BGConly-NF, and BGC-DV-F minus BGC-DV-NF). Asterisk (\*) index indicates**  
 588      **that the difference passed the Student's t test at the  $\alpha = 0.05$  significance level.**

BGConly			BGC-DV			
	BGConly-F	BGConly-NF	Difference	BGC-DV-F	BGC-DV-NF	Difference
LAI	2.13	2.36	-0.23*	2.24	2.62	-0.38*
Height	7.05	7.45	-0.4*	6.03	7.76	-1.73*

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**Table 7: Annual mean soil moisture (%) at each soil depth and the difference between with fire and without fire cases (i.e., BGConly-F minus BGConly-NF, and BGC-DV-F minus BGC-DV-NF). Asterisk (\*) index indicates that the difference passed the Student's t test at the  $\alpha = 0.05$  significance level.**

Depth	BGConly			BGC-DV		
	BGConly-F	BGConly-NF	Difference	BGC-DV-F	BGC-DV-NF	Difference
0.71 cm	21.22	21.22	0.00*	20.48	20.73	-0.25*
0.79 cm	23.22	23.15	0.07*	22.59	22.63	-0.04*
6.23 cm	23.24	23.14	0.10*	22.61	22.58	0.03*
11.89 cm	22.72	22.58	0.14*	22.14	22.06	0.08*
21.22 cm	22.37	22.2	0.17*	21.83	21.7	0.13*
36.61 cm	22.48	22.28	0.20*	21.98	21.78	0.2*
61.98 cm	22.57	22.35	0.22*	22.1	21.85	0.25*
103.8 cm	22.45	22.21	0.24*	21.95	21.7	0.25*

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