

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

This paper is evaluating the impact of incorporating fire and dynamic vegetation in the Community Land Model (CLM). The paper presents a clear description of the impact of including each of these processes by considering the change in burned area, vegetation cover, carbon balances (net ecological production and net ecosystem exchange) and water balances (evapotranspiration, runoff and soil moisture). The structure of the paper is logical and easy to follow. The method employed for this study is a set of four experiments with and without dynamic vegetation and with and without fire, which seems a valid way of testing the impact of each of these processes. However, while the paper starts well and includes a good introduction, the model description and experimental design needs more detail, and the analysis is ambiguous in several places. Specific comments on this are outlined below. The experiments here are not particularly novel, with fire and dynamic vegetation having been implemented in this model for several years as cited in the paper, but it is useful to have an evaluation of the impact of both processes as they are both important in land-surface and Earth System modelling. I recommend resubmission subject to addressing the following points.

Specific Comments

1) The BGConly model can be run with and without fire, and the results show that aspects of the vegetation (GPP, NPP, NEP etc, Table 3) are impacted when fire is included. But in the model description it says that the spatial distribution of PFTs is set using satellite data from MODIS and that a whole-plant mortality rate of 2% annually is assumed, rather than being determined by heat stress and fire etc. as it is in the dynamic vegetation model. So presumably the fire effects some aspects of the carbon cycle in the BGConly model, but not vegetation cover? I think this needs some clarification in the model description section – exactly what aspects are modified by including fire in the BGConly model, and what is not. It may be that this process is described in another paper, but it is necessary to understand this for the rest of this paper so it should be outlined here.

>> As per reviewer's suggestion, we have clarified what aspects are influenced by fire in BGConly as well as in BGC-DV in the revised manuscript as follows.

L96: *"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 in LAI (Castillo et al., 2012; 2013)."*

L118: *“Burned area also impacts the carbon and nitrogen pools of the vegetation, which are related to leaf, stem, and root; fire changes the vegetation state (e.g., LAI) and vegetation height during the burning period in both BGConly and BGC-DV runs. However, the number of individual PFTs does not change in BGConly, but decreases by biomass burning in BGC-DV. In other words, individual plants are killed by fire only when the DV option is included in the model.”*

2) Related to the previous point, the BGConly-F results (Figure 3) are at one point referred to as ‘observations’ (line 175). This may be the case in terms of vegetation cover if this is prescribed and not altered by fire, but in the rest of the paper this is one of the experimental runs being evaluated, so it needs to be clearly stated that this exactly the same as the satellite data, both in BGConly-F and BGConly-NF, and it is therefore valid to treat this as observations. The labelling throughout the text is also quite confusing which doesn’t help. For example the label ‘BGConly’ on Figure 3b doesn’t specify if this is the fire on or off run, and ‘BGConly’ is first described as the non-dynamic vegetation option (line 99) and then later as the impact of fire ‘BGConly-F minus BGConly-NF’ for figure 6 onwards (line 207).

>> We have clarified that the same land cover is used in BGConly-F and BGConly-NF runs using the observations (i.e., MODIS) in the caption of Figure 3.

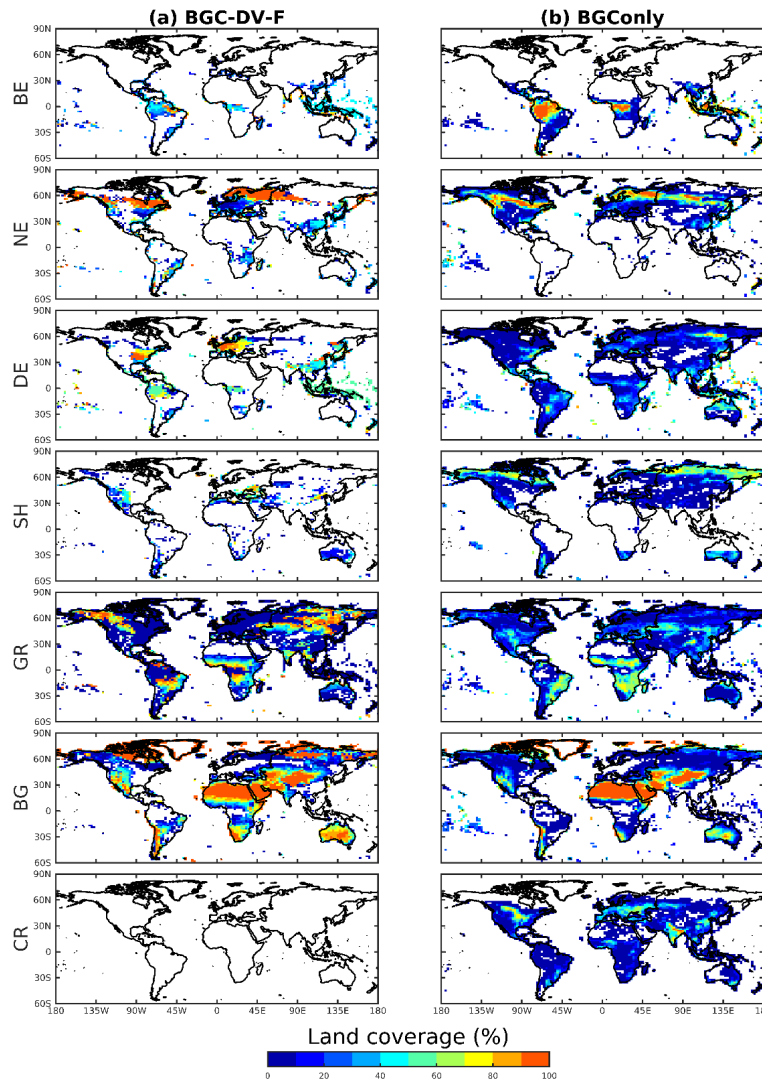


Figure 3: “Percentages of land cover type (broadleaf evergreen (BE), needleleaf evergreen (NE), deciduous (DE), shrub (SH), grass (GR), bare ground (BG), and crop (CR)) in BGC-DV-F and BGConly (the same for both BGConly-F and BGConly-NF).”

>> To clarify the confusing labels, we have revised all the related text as well as the captions of Figures 6, 7, 8, and 9 in the revised manuscript as follows:

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.”

L261: “The impact of fires on water balance was examined by estimating the changes in runoff, evapotranspiration, and soil moisture between the 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).”

Figure 6: “Differences in carbon emissions (C_{fe}), net ecosystem production (NEP), and net ecosystem exchange (NEE) due to fire 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 difference passed the Student's *t*-test at the 0.05 significance level. Latitudinal mean differences are plotted in the far-right column.”

Figure 7: “Differences in net ecosystem production (NEP), net primary productivity (NPP), and heterotrophic respiration (R_h) due to fires in BGC-DV (i.e., BGC-DV-F minus BGC-DV-NF) according to the percent changes in bare ground (BG), needleleaf evergreen (NE), and grass (GR) vegetation types.”

Figure 8: “Differences in evapotranspiration (ET) and runoff 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 the far-right column.”

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

3) The method for calculating NEP should be included, probably before equation (3) for NEE

>> We have added the explanation of NEP in the revised manuscript.

L129: “The terrestrial carbon balance is affected when biomass is burned. The net ecosystem exchange (NEE) can be estimated using NEP ($NEP = NPP - \text{heterotrophic respiration } (R_h)$) and carbon loss due to biomass burning (C_{fe}).”

4) The GFED3 dataset is used here for evaluating the burned area, but there are more up to date datasets now including small fires such as GFED4.1s. Is there a reason why GFED4.1s was not used here?

>> We have used the GFEDv4 and GFEDv4s as well as GFEDv3 for comparisons with our results. We have revised the relevant paragraph and Figure 2 with GFEDv4s (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⁻¹ for 1997–2009, 348 Mha yr⁻¹ for 1997–2011 and 513 Mha yr⁻¹ 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⁻¹) similar to that of GFED3 (i.e., 371 Mha yr⁻¹).”

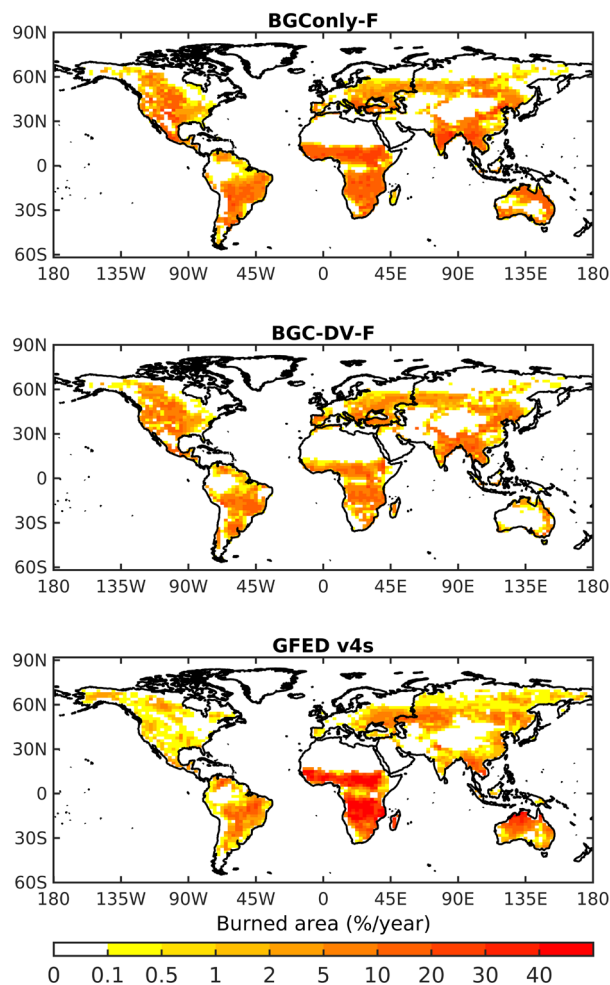


Figure 2: “Annual burned area percentage by grid cells for CLM4.5BGC with fire (BGConly-F), CLM4.5BGCDV with fire (BGC-DV-F), and Global Fire Emission Database version 4 with small fires (GFEDv4s).”

5) It seems strange that the original fire model was designed to consider vegetation dynamics (line 69) and the fire model is always run with BGC-DV (line 144), and that it simulates agricultural fire (line 105), but the DV model doesn’t include crops (line 162). Presumably the agricultural fire function is only available in BGConly mode? This also needs explaining in the model description.

>> To explain that crop PFTs were 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.”

Table 1: Configurations of experiments used in study.

	BGC for year 1850	BGC for 20th century	BGC only	BGC-DV
Time	-	1901–2000	200 yr	200 yr
Climate forcing (CRU-NCEP) [CO ₂]	Repeated 1901– 1920 1850	1901–2000	Repeated by 5 times 1961–2000	Repeated by 5 times 1961–2000
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)

6) ξ is the whole-plant mortality factor for each PFT (Line 120). What are the values of this

factor and how is it determined?

>> We have added the details of the whole-plant mortality in the revised manuscript as follows.

L126: *“The whole-plant mortality, the rate at which plants die completely by fire, is a calibrated PFT-dependent parameter, which is 0.1 for broadleaf evergreen trees, 0.13 for needleleaf evergreen trees, 0.07 for deciduous trees, 0.15 for shrubs, and 0.2 for grasses (Li et al., 2012).”*

7) Line 134 states that ‘the final surface conditions should represent those of the year 2000 after running the transient simulation’. This is fine, but line 141 states ‘In these simulations, the initial global land state was bare ground. . . and soil conditions. . . were adjusted to those of the year 2000’. Does this mean the initial land state was bare ground at the start of the transient simulation, not reset at 2000? I’m not sure why you would reset vegetation at 2000 after doing a transient run, so this is probably a wording issue, but then why adjust soil conditions to 2000? I would also have expected a spin-up at the beginning considering the initial state is bare soil, to equilibrate soil and vegetation carbon at 1850. What climate is used for this 200-y run, is it a climatology at 2000? I’m not sure that the 200-y simulations result in ‘potential land surface conditions’ (line 151-152), but rather an equilibrium state?

>> There was a mistake in the original manuscript about the time period of the climate forcings. We have 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 L223 and added to Table 1 in the revised manuscript.

>> While BGConly runs are initialized with vegetation, restarting from the end of the BGC 20th century transient run, BGC-DV runs are initialized with no vegetation with soil conditions, restarting from the end of BGC 20th century transient run. We marked these on Table 1 to avoid misleading sentences. 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 (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 stabilization. This point has been clarified in the revised manuscript as follows.

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.”*

>> As suggested, we have corrected “potential” to “equilibrium” in L168.

8) Line 273 states ‘We therefore expect that the impact of fire on precipitation would be more significant in BGC-DV than in BGConly because fire directly influences land cover characteristics’; is this the case even though it states prior to this that Li and Lawrence (2017) found that the impact of fire on precipitation is limited? (line 251)? Perhaps they were not using dynamic vegetation, in which case it is worth making this point.

>> As per reviewer’s suggestion, we have revised the paragraph to clarify the implications of the small changes in ET and runoff and highlight the limitations of Li and Lawrence (2017).

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.”*

9) Line 214 states that carbon emissions from BGConly and BGC-DV are ‘relatively high’ but ‘fall within the range of previous findings’. However BGConly emissions of 3.4 PgC are not within the range of 1.9-3.0 PgC given.

>> We have added the example of Li et al. (2012) with the estimated carbon emissions of 3.5 Pg C yr⁻¹.

L231: *“For example, 1997–2014 GFED4s data estimated annual direct carbon emissions as 2.3 Pg. Mouillot et al. (2006) estimated annual carbon emissions as 3.0 Pg for the end of the 20th century and the 20th century average as 2.5 Pg. Li et al. (2012) estimated the 20th century emissions as 3.5 Pg C yr⁻¹ using the CLM3-DGVM and Li et al. (2014) and Yue et al. (2015) both estimated the 20th century emissions as 1.9 Pg C yr⁻¹ using the CLM4.5 and ORCHIDE land surface models, respectively.”*

10) In a few places the text is vague and confusing, and could do with more explanation. E.g.: Line 15: ‘This study shows that inclusion of dynamic vegetation enhances carbon emissions from fire by reducing terrestrial carbon sinks; however, this effect is somewhat mitigated by the increase in terrestrial carbon sinks when dynamic vegetation is not used’ – this seems like a circular argument, carbon emissions are either enhanced by DV compared to no DV, or they are reduced by no DV compared to DV.

>> We have modified the phrase to clarify the original meaning in the revised manuscript.

L15: *“Carbon emissions from fires are enhanced by reduction in NEP when vegetation dynamics are considered; however, this effect is somewhat mitigated by the increase in NEP when vegetation dynamics are not considered.”*

Line 193: ‘Areas that experience a higher frequency of fire occurrence have larger vegetation distribution differences, which suggests that fire has an influence on vegetation mortality’ – we know that fire influences vegetation mortality, isn’t this is point of the paper?

>> This statement has been removed from the original manuscript.

Line 197 ‘However, there are no marked changes in the fractions of shrubs and deciduous trees in the middle of the ecological succession process with respect to the presence or absence of fire’ - Specify that this is global totals, otherwise the following lines seem to contradict this.

>> We have specified it as “global fractions”.

L255 *“However, there are no significant changes in the global fractions of shrubs and deciduous trees in the middle of the ecological succession process with respect to the presence or absence of fires.”*

Line 198-200: ‘When fire occurs in a region where shrubs grow, the ratio of shrubland is diminished, but fire increases the ratio of shrubland in regions where trees may evolve from shrubs. In the same way as shrubs, the deciduous trees are increased or decreased due to fire’ – I’m lost as to where and how fire increases shrubs and deciduous trees.

>> We have explained the argument by revising the sentence and pointing out the specific regions as it follows.

L 216: *“When a fire occurs in a region where shrubs grow, the ratio of shrubland is diminished (e.g., in the middle of North America in Figure 4b), but fire increases the ratio of shrubland in regions where trees grow (e.g. in the southwestern Asia in Figure 4b).”*

Technical Corrections

1) Clarify labels for BGConly (see point 2 above).

>> To clarify the confusing labels, we have revised the captions of Figures 6, 7, 8, and 9 in the revised manuscript.

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) runs. 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.”

Figure 7: “Differences in net ecosystem production (NEP), net primary productivity (NPP), and heterotrophic respiration (R_h) due to fires in BGC-DV (i.e., BGC-DV-F minus BGC-DV-NF) according to the percent changes in bare ground (BG), needleleaf evergreen (NE), and grass (GR) vegetation types.”

Figure 8: “Differences in evapotranspiration (ET) and runoff due to fires in BGConly (BGConly-F minus BGConly-NF; left column) and BGC-DV (BGC-DV-F minus BGC-DV-NF; middle column) runs. 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.”

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

2) Line 150 says CRU-NCEP data from (1991-2000) was used. Should this be 1901- 2000 as stated in line 128?

>> As mentioned above, 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 L167 and added in Table 1 in the revised manuscript.

3) Lines 206-208 there is a spare bracket.

>> This part has been rewritten in the revised manuscript and thus no correction is needed.

4) What is ‘State vegetation’, line 206?

>> We have changed “state vegetation” to “static vegetation”.

5) The caption for figure 3 needs looking at. There are two references to BE, none to CR or BG, and the order should go from top to bottom. Also in the main text there is no mention of CR at all – I assume this is crop (see point 5 above).

>> “CR” in the caption of Figure 3 has been defined as crop 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).”

6) Section 3.2 begins by saying this section considers figures 3 & 4 (line 197) but the rest of

the section only refers to figures 4 and 5.

>> To avoid any confusion with the figure numbers, we have made the following corrections.

L198: *“The impact of fires on vegetation distribution is assessed by comparing BGC-DV-F and BGC-DV-NF simulations (Table 2 and Figures 4 and 5). Figure 4 shows the vegetation distribution of BGC-DV-NF (Figure 4a) and BGC-DV-F minus BGC-DV-NF (Figure 4b: Figure 4a minus Figure 3a);”*

7) Line 207 says ‘BGC-CV’ rather than BGC-DV

>> We have corrected it.

8) Line 221 ‘However, the overall NEP decrease is 2.5 Pg C y⁻¹’ – I think this should be increase if I’ve followed the paragraph correctly.

>> We have changed “decrease” to “increase”.

9) Line 210 ‘average annual emissions are higher in BGConly (3.4 Pg)’ – table 3 shows this should be 3.5 if rounding to 1d.p. as is done for BGC-DV

>> We have corrected it.

10) Vegetation types are not labelled in figure 5 caption

>> We have clarified vegetation types in the caption of Figure 5.

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

11) BE is labelled as bare ground in the caption for figure 7 but should be broadleaf evergreen. Also NEP, NPP, and Rh abbreviations should be defined fully in the caption as Net Ecosystem Production etc”.

>> We have corrected BE as broadleaf evergreen in the caption of Figure 7.

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

12) State which correlation test is used for tables 4-7.

>> As per reviewer's suggestion, we have clarified that we performed the Pearson correlation test in Table 4. In Table 5-7, we have clarified that the student's t tests were performed.

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

Table 5-7: *"Asterisk (*) index indicates that the difference passed the student's t test at $\alpha = 0.05$ significance level."*

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

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Abstract

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

Keywords

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

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 (BGOnly) and BGC with DV (BGC-DV) can be
95 configured. BGOnly 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 ($P_{distrib}$) is calculated using equation (2).

$$123 \quad P_{distrib} = \frac{A_b}{fA_g} P \xi, \quad (2)$$

124 where P is the population density for each PFT, ξ 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° longitude \times
134 2.5° 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⁻¹, 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⁻¹ 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⁻¹) 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%, 10–1%,
205 1–0.1% 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⁻¹ 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⁻¹
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 Pg C yr^{-1} in this study, which is greater than the value of 1.9 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⁻²) 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.

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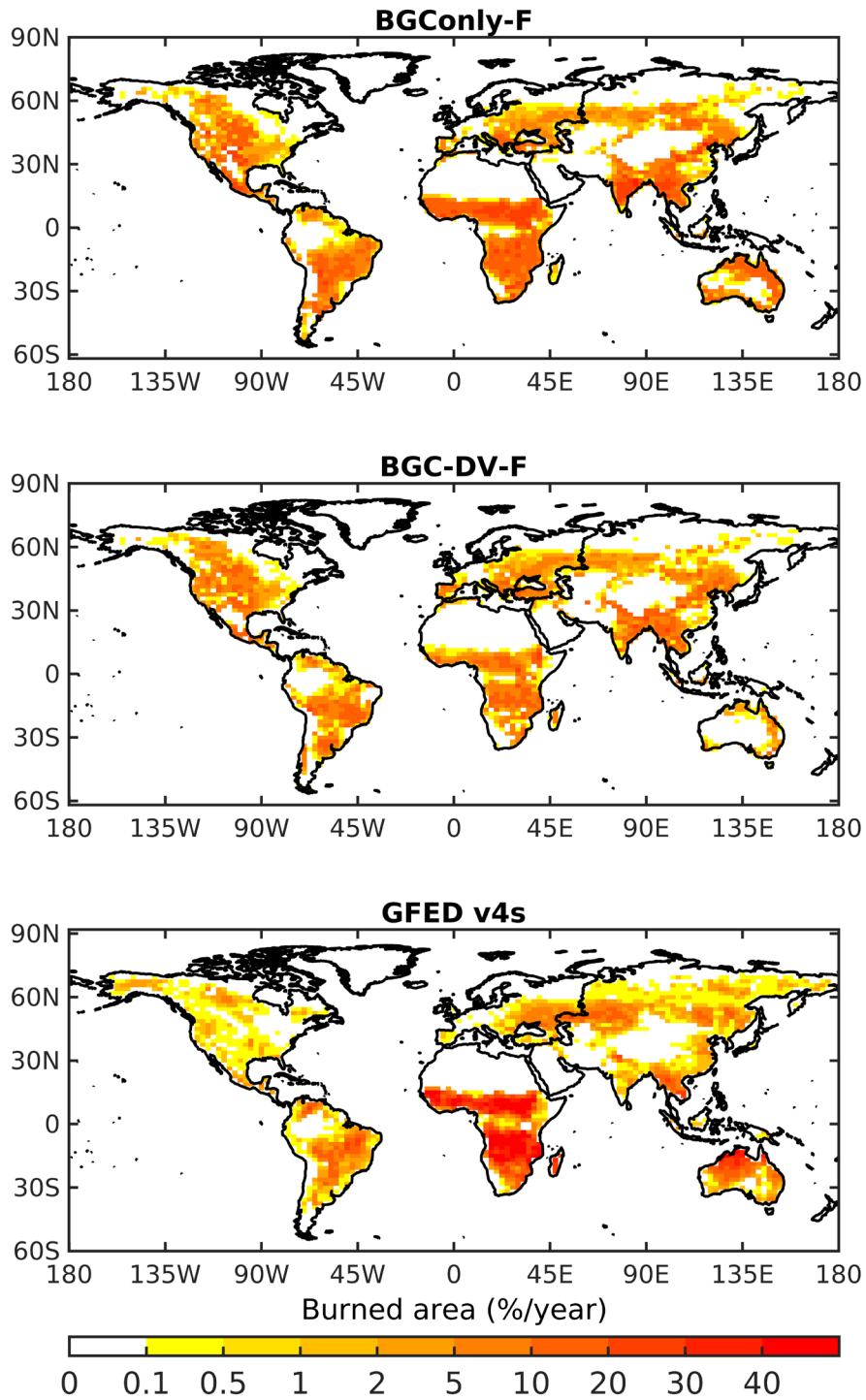
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522 **Figure 1: Flowchart showing model simulations conducted to investigate the interactive impact of fires and ecological**
523 **succession on the Earth system using Community Land Model (CLM4.5) simulations extended with biogeochemistry**
524 **(CLM4.5BGC)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

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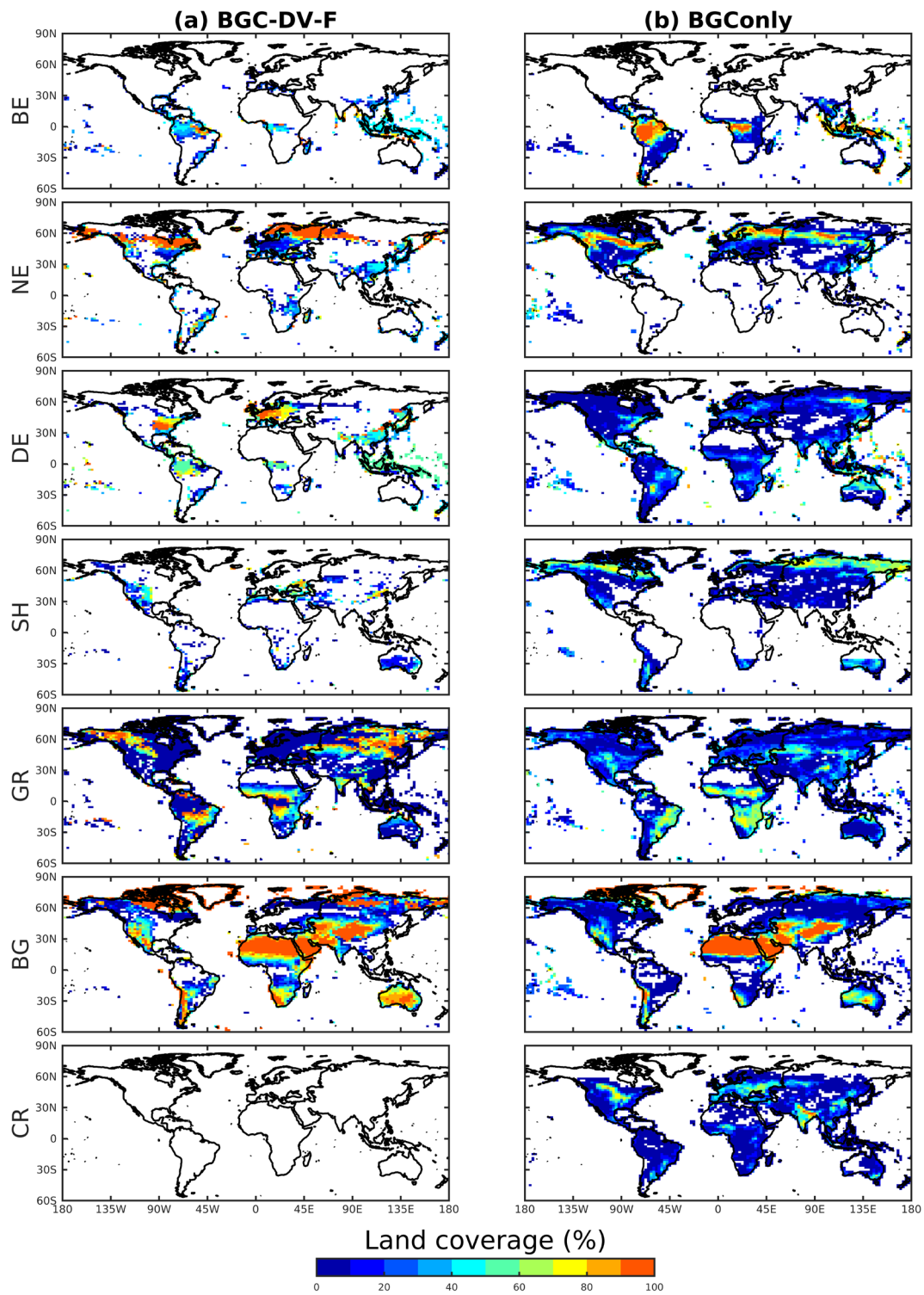
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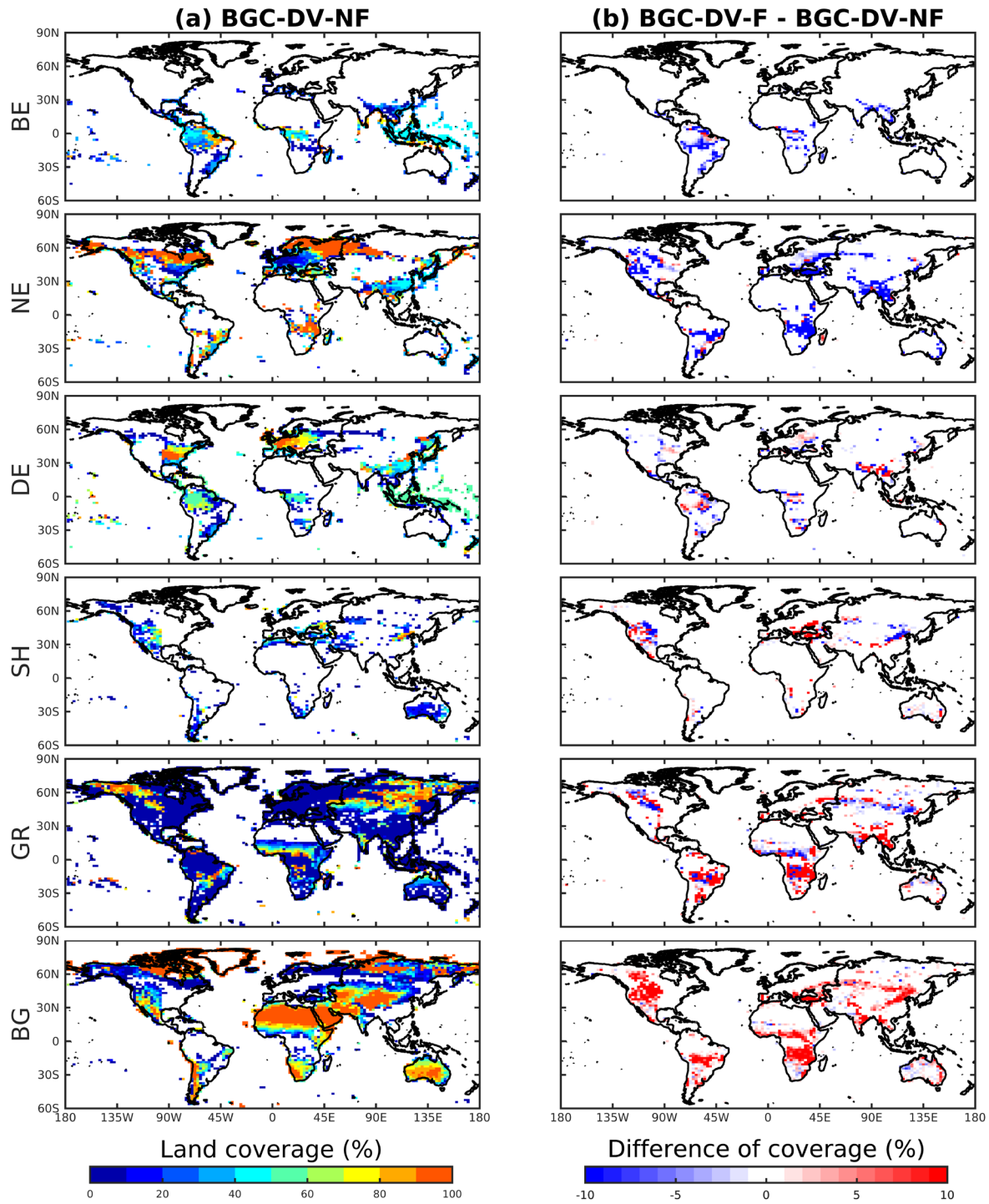
529 **Figure 2: Annual burned area percentage by grid cell for CLM4.5BGC with fire (BGOnly-F), CLM4.5BGC DV with fire**
530 **(BGC-DV-F), and Global Fire Emission Database version 4 with small fires (GFED4s)**

531



532

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

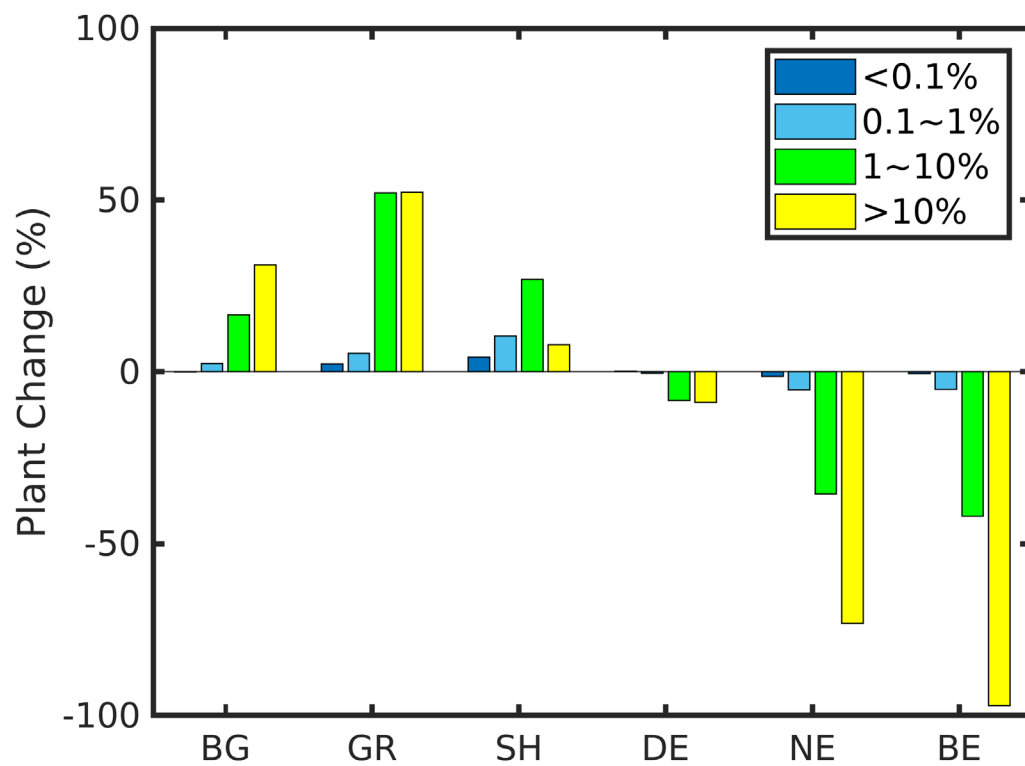


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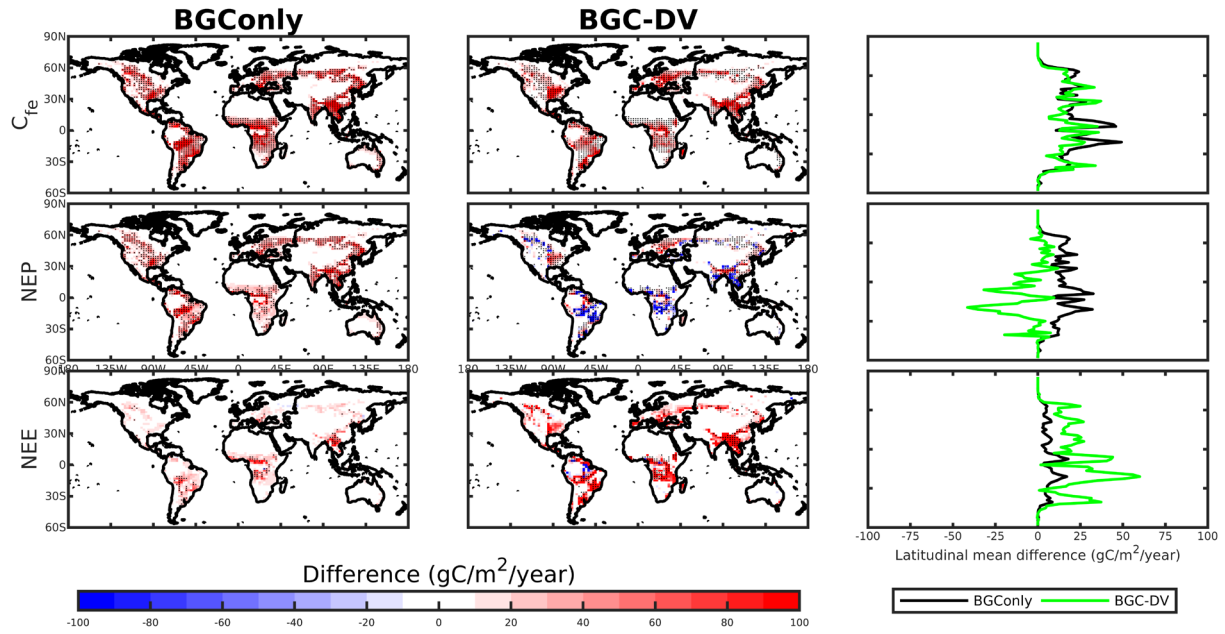
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Figure 4: Percentages of land cover (broadleaf evergreen (BE), needleleaf evergreen (NE), deciduous (DE), shrub (SH), grass (GR), and bare ground (BG)) in BGC-DV-NF and differences in plant cover between BGC-DV-F and BGC-DV-NF.



539
 540 **Figure 5: Differences in vegetation distribution (bare ground (BG), grass (GR), shrub (SH), deciduous (DE), broadleaf**
 541 **evergreen (BE), and needleleaf evergreen (NE)) ratios between BGC-DV-F and BGC-DV-NF for four burned area**
 542 **categories: under 0.1%, 0.1–1%, 1–10%, and greater than 10%.**

543



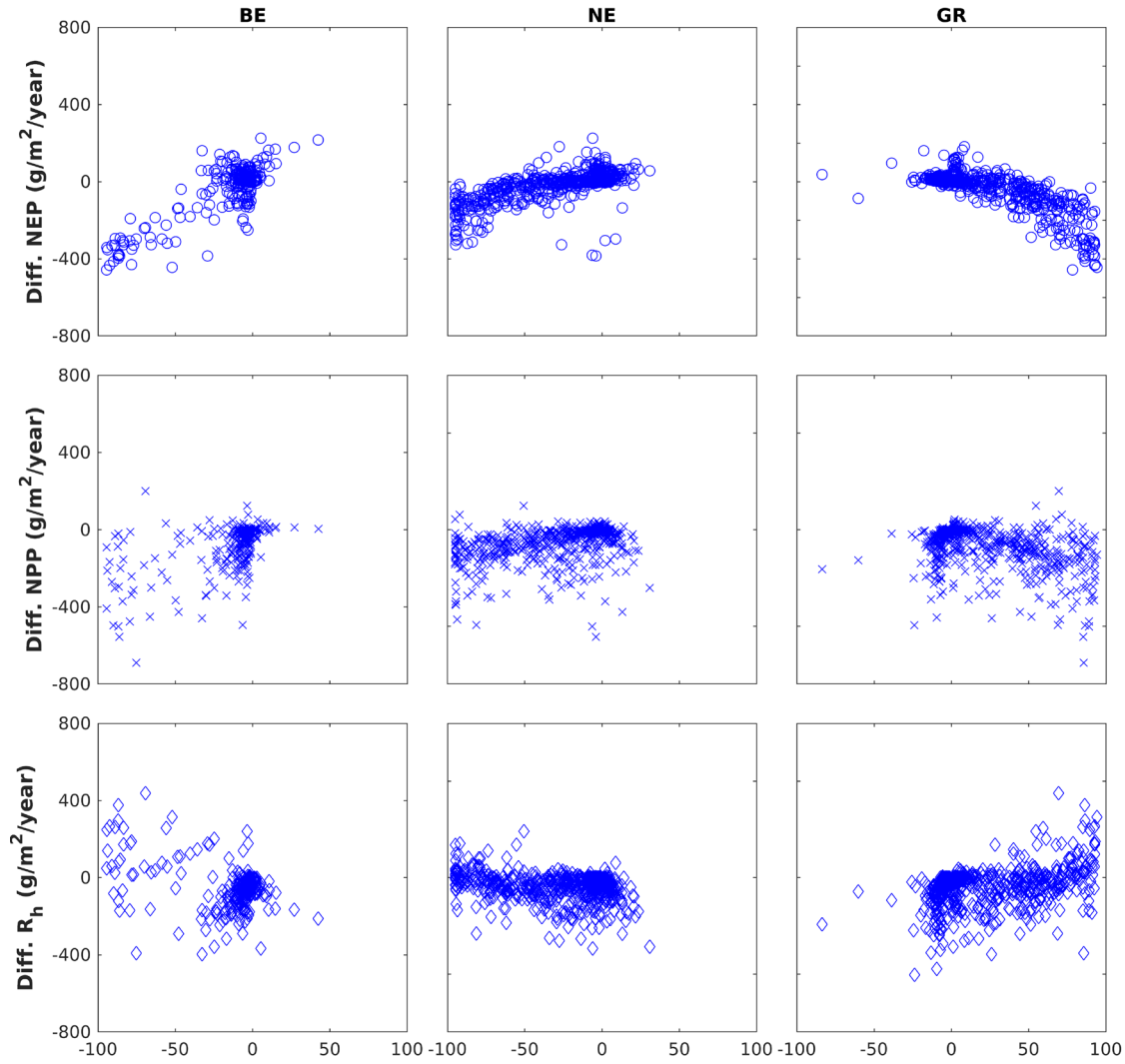
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545 **Figure 6: Differences in carbon emissions (C_{fe}), net ecosystem production (NEP), and net ecosystem exchange (NEE) caused**
 546 **by fires in BGConly (BGConly-F minus BGConly-NF; left column) and BGC-DV (BGC-DV-F minus BGC-DV-NF; middle**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

549

550

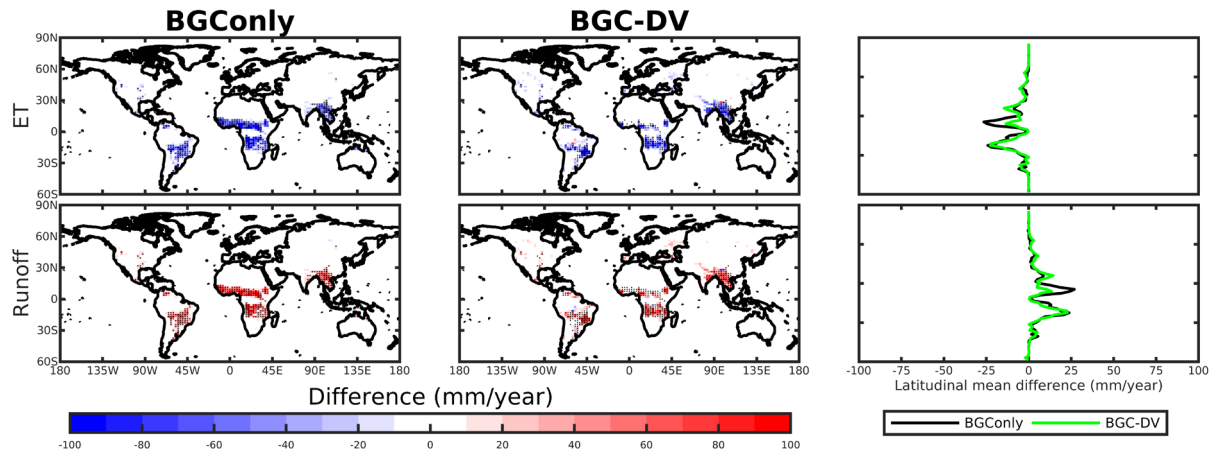
Veg. cover(%) change



551

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 **(BE), needleleaf evergreen (NE), and grass (GR) vegetation types.**

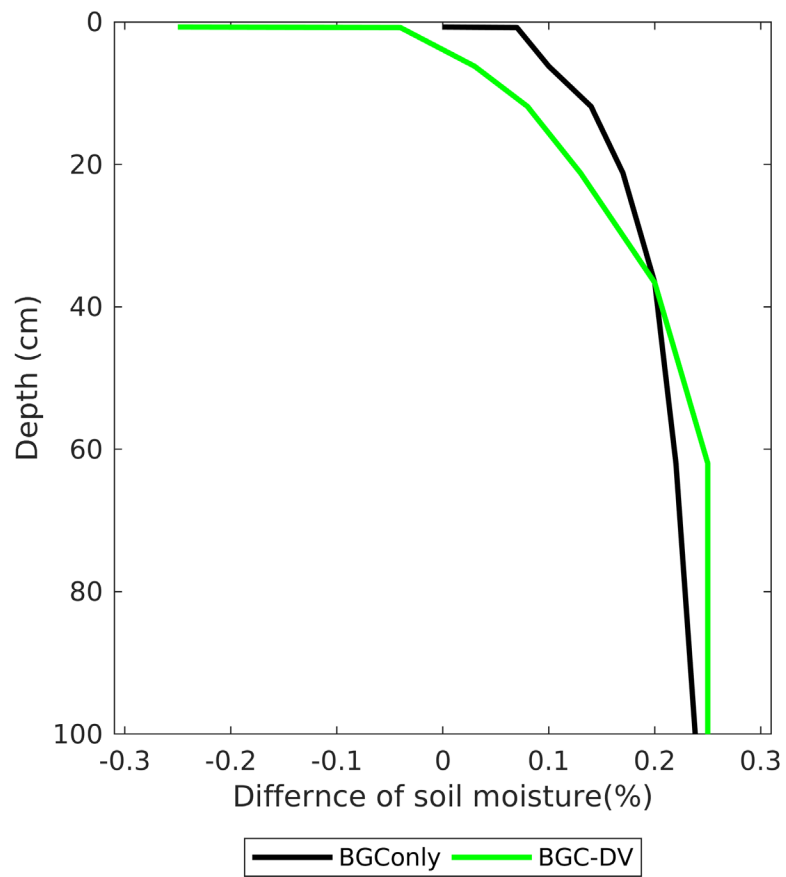
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557 **Figure 8: Differences in evapotranspiration (ET) and runoff due to fire in BGConly (BGConly-F minus BGConly-NF; left**
 558 **column) and BGC-DV (BGC-DV-F minus BGC-DV-NF; middle column). Hashed areas indicate that the difference passed**
 559 **the Student's t-test at the 0.05 significance level. Latitudinal mean differences are plotted in the far-right column.**

560



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

565 **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 ₂]	[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 BGOnly, BGC-DV-F, and BGC-DV-NF.**

	BGOnly	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	-	-

569

570

571 **Table 3: Annual means of carbon budget for GPP, NPP, R_a, R_h, NEP, NEE, and C_{fe} 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⁻¹. 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 _{fe}	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 _a	73.85	81.08	-7.23*	69.87	81.37	-11.50*
R _h	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*

574

575

576 **Table 4: Pearson correlation coefficients between carbon fluxes (NEP, NPP, R_h) and percentage changes in vegetation cover**
577 **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 _h	-0.36	-0.17	-0.01	-0.13	0.27	-0.30

578

579

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*

584

585

586 **Table 6 Annual mean values for LAI (m² 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*

589

590

591 **Table 7: Annual mean soil moisture (%) at each soil depth and the difference between with fire and without fire cases (i.e.,**
 592 **BGConly-F minus BGConly-NF, and BGC-DV-F minus BGC-DV-NF). Asterisk (*) index indicates that the difference**
 593 **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*