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.

Referee #1

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)
$[CO_2]$	???	???	???	???
Biogeog. shifts?	Yes?	Yes?	No (constant map)	Yes
Initial veg.	No (bare soil)?	Yes (as resulting 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 1961–2000	Repeated for five times 1961–2000
[CO2]	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^{-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})."*

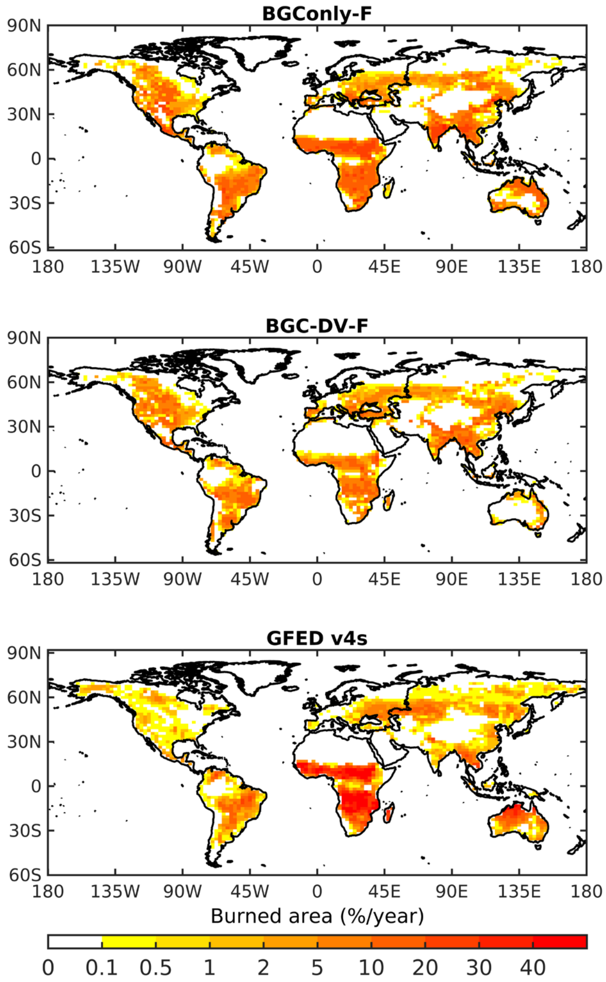

Figure 2: *"Annual burned area percentage by grid cell for CLM4.5BGC with fire (BGConly-F), CLM4.5BGCDV with fire (BGC-DV-F), and Global Fire Emission Database version 4 with small fires (GFED4s)".*

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^{-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}).*

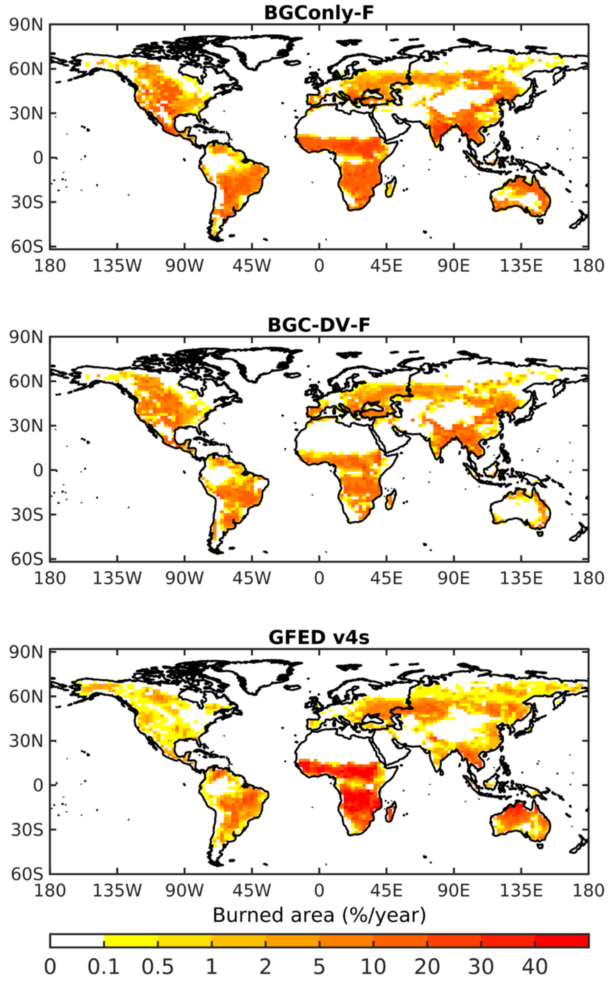

Figure 1: *"Annual burned area percentage by grid cell for CLM4.5BGC with fire (BGConly-F), CLM4.5BGCDV with fire (BGC-DV-F), and Global Fire Emission Database version 4 with small fires (GFED4s)."*

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.

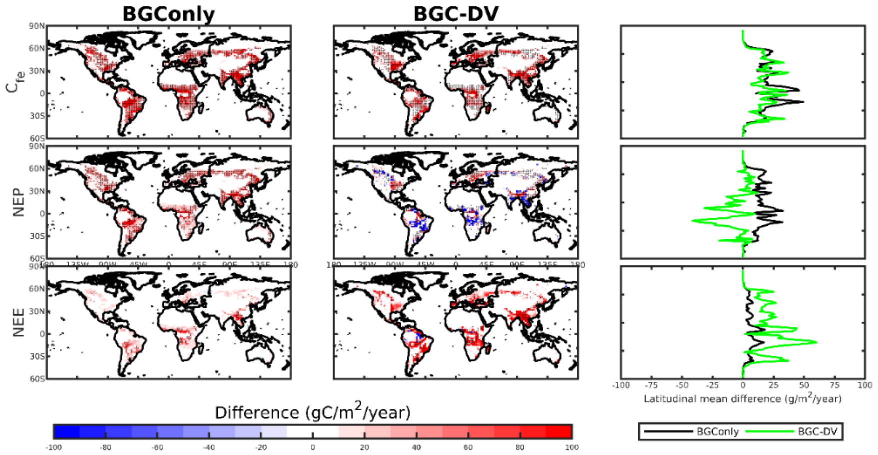

Figure 6: *"Differences in carbon emissions (Cfe), net ecosystem production (NEP), and net ecosystem exchange (NEE) due to fires in BGConly (BGConly-F minus BGConly-NF; left column) and BGC-DV (BGC-DV-F minus BGC-DV-NF; middle column). Hashed areas indicate that the difference passed the Student's t-test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

Referee #2

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.

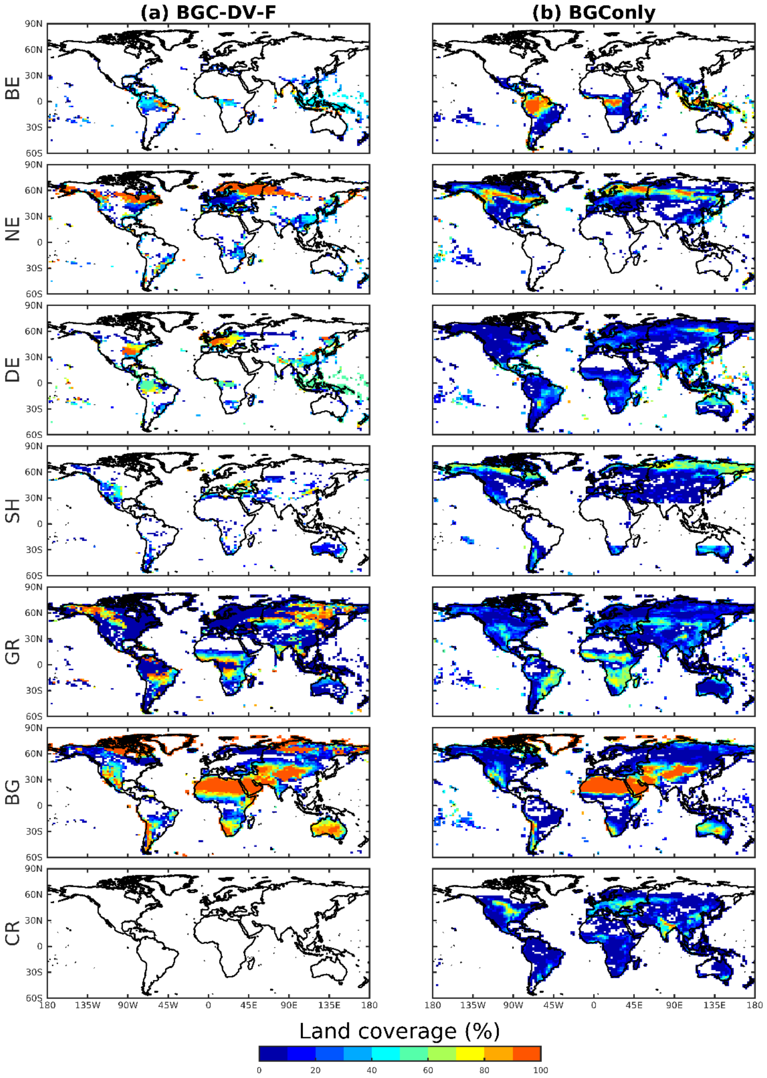

Figure 3: *"Percentages of land cover type (broadleaf evergreen (BE), needleleaf evergreen (NE), deciduous (DE), shrub (SH), grass (GR), bare ground (BG), and crop (CR)) in BGC-DV-F and BGConly (the same for both BGConly-F and BGConly-NF)."*

>> 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–heterotrophic respiration (Rh)) 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)."

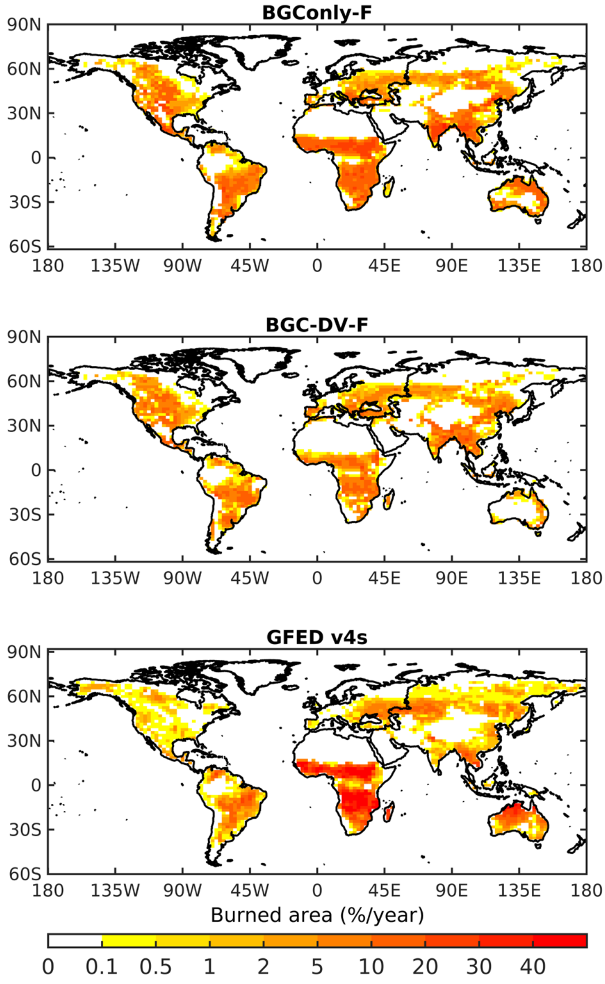

Figure 2: *"Annual burned area percentage by grid cells for CLM4.5BGC with fire (BGConly-F), CLM4.5BGCDV with fire (BGC-DV-F), and Global Fire Emission Database version 4 with small fires (GFEDv4s)."*

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 2: 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)	Repeated 1901–1920	1901–2000	Repeated by 5 times 1961–2000	Repeated by 5 times 1961–2000
[CO2]	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)

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 th 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* α *= 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

삭제됨: Impacts
삭제됨: Fire
삭제됨: Vegetation Dynamics
삭제됨: Global Carbon
삭제됨: Water Budgets

삭제됨: the
삭제됨: of vegetation.
삭제됨: the
삭제됨: land
삭제됨: utilized
삭제됨: dynamic
삭제됨: which has been shown in previous studies with the similar modeling practices. However,
삭제됨: dynamic
삭제됨: . Additionally, the carbon sink in post-fire regions reduced
삭제됨: grasses. This study shows that inclusion of dynamic vegetation enhances carbon
삭제됨: fire
삭제됨: reducing terrestrial carbon sinks
삭제됨: terrestrial carbon sinks
삭제됨: dynamic
삭제됨: is
삭제됨: used. Results also show that fire
삭제됨: ; this
삭제됨: layers compared to non-burned
삭제됨: ,
삭제됨: ignore
삭제됨: ,
삭제됨: fire
삭제됨: , particularly when
삭제됨: with respect to fire and vegetation dynamics
삭제됨: .

1 Introduction

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

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

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

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

In recent years, global fire models have become more complex (Hantson et al., 2016). Different fire models parameterize different impact factors such as fuel moisture, fuel size, probability of lightning, and human effects. 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).

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

삭제됨: Wild fire…ildfire is a natural process that influences ecosystems and the global carbon and water cycles worldwide…ycle (Gorham, 1991; Bowman et al., 2009; Harrison et al., 2010). Climate and vegetation control both …he occurrence of fire…ires and its…heir spread, which in turn affects climate and vegetation (Vilà et al., 2001; Balch et al., 2008), and when…. When fire destroys forests and grasslands, the distribution of vegetation is also affected (Clement & …

[1] 아래로 이동함: Fire

삭제됨: causes the formation…of trace gases and aerosols, which are important elements in the radiative balance of the atmosphere (Scholes et al., 1996; Fiebig et al., 2003); aerosols can…. Aerosols affect surface air temperature, precipitation, and circulation (Tarasova et al., 1999; Lau &…nd Kim, 2006; Andreae & …

삭제됨: , and… leaves and roots can be annihilated in such…hose regions (Noble et al., 1980; Swezy &…nd Agee, 1991). Each year, fire transports…ires transport approximately 2.1 Pg of carbon from soil and vegetation into the atmosphere in the form of carbon dioxide and other carbon compounds (van der Werf et al., 2010). Harden et al. (2000) postulated…eport that approximately 10–30% of annual net primary productivity (NPP) disappeared…isappears through fires in upland forests. In addition, transpiration…ranspiration and canopy evaporation decreases due to …ecrease with the reduction in leaf numbers (Clinton et al., 2011; Beringer et al., 2015). Soil has also been found to develop…evelops a water …repellent layer during fire, which is attributed…ires due to intense heating (DeBano, 1991),… and the …sh produced by biomass combustion can impact…mpacts the quality of runoff (Townsend & …

삭제됨: the process of …cological succession (Prach &…nd Pyšek, 2001). In this respect…herefore, the structure and distribution of vegetation can be altered by fire…ires in post-fire regions (Wardle et al., 1997); for example, several studies have suggested that the…. The existence of grass and trees in the savanna can be attributed to fire…ires (Hochberg et al., 1994; Sankaran et al., 2004; Baudena et al., 2010). However, fire …

삭제됨: different …spects of the Earth system. Therefore, a certain degree of …rocess-based representation of fire…ires is included in Earth system models, such as within…dynamic global vegetation models (DGVMs), land surface models (LSMs), and Earth system models (ESMs; Rabin et al., 2017). Studies have applied fire Previous studies reported the incorporation of fire models to…nto global climate models to investigate the occurrence and spread of fire…ires and how it impacts…hey impact climate and vegetation (e.g., Pechony &…nd Shindell, 2010; Li et al., 2012; 2013). For example, …ond et al. (2005) used the Sheffield DGVM (SDGVM) and performed the first global study on the extent to which fire determines…ires determine global vegetation patterns by preventing ecosystems from achieving potential height, biomass, and dominant functional types expected under an …mbient climate …

삭제됨: grown in complexity…ecome more complex (Hantson et al., 2016), and different…. Different fire models parameterize different impact factors such as fuel moisture, fuel size, the …robability of lightning, and human effects. In this respect, the Fire Model Intercomparison Project (FireMIP) evaluated …

삭제됨: known as the Community Earth System Model (CESM) has been developed and assessed within the framework of the National Center for Atmospheric Research (NCAR) the Community Earth System Model (CESM) (Li et al.,… 2012; 2013; 2014), and the latest…015). The satellite-based Global Fire Emission Database version 3 (GFED3), which is derived from moderate resolution imaging spectroradiometer …

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

삭제됨: parameterizations. Furthermore, the…arameterization. The impact of fire…ires on carbon, water, and energy balances…alance has also been investigated within the CESM framework (Li et al., 2014; Li &…nd Lawrence, 2017). However, although these studies have considered land-…atmosphere interactions with CLM…sing the Community Land Model (CLM) coupled to the…ith an atmospheric model, they have ignored the changes in global vegetation patterns due to fire processes…aused by fires, even though the initial model developed by Li et al.,… (2012) was designed to consider the vegetation dynamics (i.e., changes in vegetation distribution) within the Community Land Model (CLM)- ...…

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

삭제됨: possible influences…ndividual and combined impacts of fire processes on water and carbon exchanges…ires and vegetation distribution,…on water and their combined effects…arbon exchange; however, few studies to date have assessed this complicated global process. Therefore, in this study, we aim to understand the interactive effects of fire…ires and ecological succession on carbon and water fluxes at…n the land's…and surface. Specifically, using the NCAR CLM, we conduct a series of numerical experiments using the NCAR CLM …hat variously…include and exclude fire and dynamic vegetation processes. Our results show that the impact of fire…ires on carbon and water balances ...…

2 Model and experimental design

삭제됨: ... [...

2.1 Model description

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

삭제됨:),… and it…comprises different components such as land, atmosphere, ocean, land ice, and ocean ice (Worley at el., 2011; Kay et al., 2012). Each component utilizes various formulae to represent the complex interplay of physical, chemical, and biological processes,…and each can be used either independently or as coupled (Smith et al., 2010; Neale et al., 2012; Bonan et al., 2013). Land surface in the CLM is represented by sub-grid land cover (glacier, lake, wetland, urban, or vegetated),… and vegetation coverage is represented by 17 plant functional types (PFTs) comprising 11 tree PFTs, two… crop PFTs, three ... [...

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

삭제됨: In this study, …LM 4.5 was extended using …an be run by including different levels of vegetation processes. In the biogeochemistry (BGC) model…atellite phenology (SP) option; this configuration simulates the carbon… vegetation coverage and nitrogen cycles in addition to biophysics and hydrology ... [...

[2] 아래로 이동함: (Paudel et al., 2016).

삭제됨: In CLM with BGC,…the spatial distribution of …atellite-derived climatological data. The coverage of different PFTs is set using monthly …limatological satellite …ata (Lawrence &…nd Chase, 2007), which differs between months but not between years. Climatological PFT data are conserved based on…erived from a variety of satellite products including MODIS and Advanced Very High-Resolution Radiometer data. Land fractions are divided into bare ground, grass, shrub, and evergreen/deciduous tree types…rees. In addition, grass, shrub, and tree PFTs are classified into tropical, temperate, and boreal types, based on the physiology and climate rules of Nemani et al. (1996). Vegetation is further divided into C3 or C4 plants based on MODIS …derived leaf area index (…AI) ... [...

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

삭제됨: Certain BGC simulations were run…n 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- ... [...

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.

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

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

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

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

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. The number of PFTs killed by fire ($P_{distrub}$) is calculated using equation (2).

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

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 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 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 grass (Li et al., 2012).

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

$$NEE = -NEP + C_{fe} \qquad (3)$$

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2.2 Experimental design

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

Using the simulated surface conditions for the year 2000, four different 200 yr equilibrium CLM simulations (BGConly and BGC-DV simulations with and without the fire model) were conducted (Table 1). For BGConly runs, a restart file from the transient run was used with and without the fire model (hereafter, BGConly-F and BGConly-NF, respectively). Similarly, the BGC-DV runs were performed using the same restart file to simulate the equilibrium vegetation in 200 yr offline BGC-DV runs both with and without the fire model (hereafter, BGC-DV-F and BGC-DV-NF, respectively; Erfanian et al., 2016). 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. While the fire model is optional when using CLM with BGC, it is always run when using CLM with BGC-DV. Hence, the model was modified when conducting the BGC-DV-NF run and the burned area was set to zero to neglect any fire incidences.

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

3 Results and discussion

3.1 Burned area

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

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

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

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).

3.2 Interactions between vegetation and fire processes

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). The plots clearly indicate large differences in vegetation cover in areas of high fire frequency (i.e., South Africa, South America, western North America, India, and a portion

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

We estimated the fraction of burned areas where fractions are grouped into four categories (>10%, 10–1%, 1–0.1% and, <0.1%) for each vegetation type, and investigated the relationship between vegetation distribution and fire occurrence. 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%). However, relatively large changes in vegetation distribution occur when the burned area fraction exceeds 1%. Furthermore, there are large changes in the vegetation distribution in areas with burned area fractions above 10%, including increases in bare ground, grass, and shrubs (31.19, 52.28, and 7.91%, respectively) but decreases in deciduous, needleleaf evergreen, and broadleaf evergreen trees (8.85, 79.22, and 91.17%, respectively).

In ecosystems, plants die in regions where fires occur and grass with rapid growth rates occupies those regions. Therefore, fire increases the ratio of bare ground and grassland but reduces the number of trees. However, there are no significant changes in the global fraction of shrubs and deciduous trees in the middle of the ecological succession process with respect to the presence or absence of fires (Table 2). 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). Similarly, the number of deciduous trees increases or decreases due to fires. Thus, the role of fires in areas of shrubland and deciduous trees varies with the region and the actual vegetation distribution is a result of many factors including fire, climate, topography, and soil conditions (He et al., 2007; Cimalová and Lososová, 2009).

3.3 Fire impact on carbon balance

The direct and indirect impacts of fires on carbon balance were investigated for static and dynamic vegetation cover (Figure 6 and Table 3). 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.

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

Carbon emission estimates from both BGConly and BGC-DV simulations are relatively high; however, they do fall within the range of previous findings. 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.

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

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삭제됨: The relationship between vegetation distribution and fire occurrence is investigated by estimating…e estimated the fraction of burned areas (Figure 5),… where fractions are grouped into four categories (>10%, 10%~…1%, 1%~…0.1% and, <0.1%) for each vegetation type, and they…nvestigated the relationship between vegetation distribution and fire occurrence. 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. Changes in the vegetation distribution…he changes are small in areas with minimal fire occurrence or where the burned area fraction is small (0.1~…1%). However, relatively large changes in vegetation distribution are apparent

삭제됨: Areas that experience a higher frequency of fire occurrence have larger vegetation distribution differences, which suggests that fire has an influence on vegetation mortality. …n ecological processes…cosystems, plants die in regions where fire occurs; grasses…ires occur and grass with rapid growth rates then occupy…ccupies those regions after fire… Therefore, fire increases the ratios…atio of bare ground and grassland but reduces the percentage …umber of trees. However, there are no marked…ignificant changes in the fractions…lobal fraction of shrubs and deciduous trees in the middle of the ecological succession process with respect to the presence or absence of fire…ires (Table 2). 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 may evolve from shrubs. In the same way as shrubs, …row (e.g., in the southwestern Asia in Figure 4b). Similarly, the number of deciduous trees are increased…ncreases or decreased…ecreases due to fire…ires. Thus, it is apparent that …he role of fire…ires in areas of shrubland and deciduous trees differs according to…aries with the region,…and the actual vegetation distribution is a result of complicated…any factors that include…ncluding fire, climate, topography, and soil conditions (He et al., 2007; Cimalová &

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삭제됨: fire…ires on carbon balances…alance were investigated by exploring the difference between fire impact when using state…or static and dynamic vegetation cover (Figure 6 and Table 3). The impact of fire in two cases (…ires in BGConly was estimated by calculating the difference between BGConly-F minus…nd BGConly-NF (BGCOnly) and BGC-DV-F minus BGC-DV-NF (BGC-CV) were estimated by averaging… averaged over the final 30-y…years of each 200-y

삭제됨: due to fire…rom fires (direct impacts) are shown in Figure 6. The spatial distributions …istribution of the BGConly and BGC-DV runs are…s similar, but average annual emissions are higher in BGConly (3.4… Pg) compared to…han in BGC-DV (3.0 Pg). This result could be attributed to… because trees being…re less dominant in BGC-DV compared to…han in BGConly, which thus

삭제됨: We note that…arbon emission estimates of carbon emissions …rom both BGConly and BGC-DV simulations are relatively high; however, they do fall within the range of previous findings. For example, 1999–2011 GFED3…997–2014 GFED4s data estimated annual direct carbon emissions as being approximately 2.0….3 Pg. Furthermore, …ouillot et al. (2006) estimated annual carbon emissions as being approximately ….0 Pg for the end of the 20th century and approximately 2.5 Pg for …he 20th century average; and…as 2.5 Pg. Li et al. (2014) and Yue et al. (2015) both…012) estimated the 20th century emissions as being

삭제됨: , as shown in …(Figure 6.…. Fire increases the NEP in post-fire regions in BGConly simulations, between BGConly-F and BGConly-NF, Figure 6a), which is consistent with the findings of the previous studies (Li 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} calculated by Li et al. (2014). However, Li et al. (2014) performed a transient simulation from 1850 to 2004, whereas the BGConly runs in our study were conducted following an equilibrium simulation using the year 2000 as the reference year, which means that no fire exchanges are caused by land cover changes.

삭제됨: However, the…he overall NEP decrease…ncrease is 2.5 Pg C y…r^{-1} in this study, which is greater than the value of 1.9 Pg C yr^{-1} determined…alculated by Li et al. (2014). However, Li et al. (2014) performed a transient simulation from 1850 to 2004, whereas the BGConly runs in our study were conducted following an equilibrium simulation using the year 2000 as the reference year, which thus meant…eans that no fire exchanges were due to

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).This carbon sink reduction occurs in regions where dominant PFTs change from broadleaf and needleleaf evergreen trees to grass (Table 3 and Figure 6). Table 4 shows the correlation coefficients between percent changes in vegetation types and changes in carbon fluxes (NEP, NPP, and R_h) for six different PFTs in each grid cell, and Figure 7 shows the broadleaf evergreen tree, needleleaf evergreen tree, and grass PFTs. NEP changes are strongly linked to changes in dominant PFTs; for example, decreases in broadleaf evergreen and needleleaf evergreen trees and increases in grass. Furthermore, the changes in NEP and PFTs are related to the changes in NPP and R_h to some extent. Our results differ from those of previous studies that did not consider vegetation dynamics (e.g., Amiro et al., 2010) because the inclusion of vegetation dynamics enables the model to capture NEP decreases in post-fire regions at the beginning of the post fire-succession.

삭제됨: when using…n BGC-DV (…imulations (i.e., differences between BGC-DV-F and BGC-DV-NF, Figure 6). …b).This carbon sink reduction occurs in regions where dominant PFTs changed…hange from broadleaf and needleleaf evergreen trees to grasses (as shown in …rass (Table 3 and Figure 6). Table 4 shows the correlation coefficients between percentage…ercent changes in vegetation types and changes in carbon fluxes (NEP, NPP, and heterotrophic respiration (…$_h$))… for six different PFTs in each grid cell),…and Figure 7 shows the broadleaf evergreen tree, needleleaf evergreen tree, and grass PFTs. It is apparent that …EP changes are strongly linked to changes in the …ominant PFTs; for example, decreases in broadleaf evergreen and needleleaf evergreen trees,…and increases in grasses…rass. Furthermore, associations between …he changes in NEP and PFTs are related to the changes in both…NPP and R_h to some extent. Our results differ from those of previous studies that did not consider vegetation dynamics (e.g., Amiro et al., 2010),

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

삭제됨: As…ince land use change is…hanges are not considered in this study, the overall impact of fire…ires was estimated by the sum of direct carbon emissions from fires and terrestrial carbon sinks, i.e., NEP (Eq. 3). Both simulations resulted in net carbon sources in the post-fire regions, even though different processes were involved. Although…irect carbon emissions due to fire…rom fires (C_{fe} in Eq. 3) were partly negated by the increased terrestrial carbon sinks…EP in the BGConly runs, but they were enhanced by the reduction in terrestrial carbon sinks…f NEP in the

3.4 Fire impact on water balance

삭제됨:

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). Increases in runoff and decreases in evapotranspiration (ET) were observed in post-fire regions to a different degree, which is consistent with the results of the previous studies (Neary et al., 2005; Li and Lawrence, 2017). Our study used CLM as a standalone model without coupling it with atmospheric or ice models, whereas Li and Lawrence (2017) examined the impact of fires on global water budget using CLM-BGC coupled with the CAM and CICE models and showed that the impact of fires on global annual precipitation was limited.

삭제됨: fire…ires on the…water balance was examined by estimating the changes in runoff, evapotranspiration, and soil moisture, …between cases with and by making a comparison…ithout 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). Increases in runoff and decreases in evapotranspiration (ET) were found…bserved in post-fire regions to a different degrees…egree, which is consistent with the results of the previous studies (Neary et al., 2005; Li &…nd Lawrence, 2017). Our study used CLM as a standalone model without coupling to the…t with atmospheric or ice models, whereas Li and Lawrence (2017) examined the impact of fire…ires on the…global water budget using CLM-BGC coupled with the CAM and CICE models and found…howed that the impact of fire

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

삭제됨: pointed out…emonstrated that a reduction in the …egetation canopy (LAI; Table 6) is a critical pathway for fire impacting on ET and leading to its…ires that decrease ET. Fire events lower the leaf area, which decreases vegetation transpiration and canopy evaporation; however, they also expose more of the soil to the air and sunlight, which increases soil evaporation. Post-fire decreases in vegetation height (Table 6) can both …ncrease and decrease

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

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

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.

4 Conclusions

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

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

삭제됨: exchanges…xchange and leads to higher leaf temperatures and wind speeds. In this study, both BGConly and BGC-DV runs show that the vegetation canopy is the main pathway leading to ET… decrease in ET, which is similar to the findings of Li and Lawrence (2017). In addition, an examination of how…he changes in the vegetation composition within…n post-fire regions influences the above mechanisms …hows that the overall impacts…mpact of those changes in ET and runoff do…oes not differ greatly when dynamic vegetation is employed by…n the model. However,

삭제됨: marked…ignificant decrease in canopy transpiration and increased…ncrease in soil evaporation relative to BGConly runs. Fire destroys plant roots and leaves, and… changes in the dominant vegetation types in BGC-DV lead to changes in the soil moisture profile through reduced transpiration (Figure 9 and Table 7). Consequently, there is less water stress in each soil layer within…n the burned areas than in non-burned…nburned areas. Grasslands dominate in…he post-fire regions when using…n BGC-DV,…runs and they absorb and transpire more water from the top soil layer compared to…han trees (Mazzacavallo &…nd Kulmatiski, 2015). There…herefore, there is thus…less moisture in the top soil layers in fire affected regions than in non-burned…nburned regions, despite the fact that…lthough the overall transpiration is diminished. Put simply…n summary, fire has an impact on the

삭제됨: Changes …espite the differences in soil moisture and vegetation canopy and height, changes in ET and runoff do not differ markedly…ary significantly 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 … Thus, including dynamic vegetation does not allow for …mpact 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. We therefore expect that the impact of fire…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 more significant in BGC-DV than in BGConly because fire directly influences land cover charac

삭제됨: .

삭제됨: of…etween the vegetation dynamics and fire impacts…he impact of fires, we conducted a series of numerical experiments using CLM both …ith and without fire…ires and dynamic vegetation processes enabled… In particular, we investigated fire influences…he impact of fires on vegetation distribution,…and how such

삭제됨: As expected,…he results showed…how that fire interrupts the process of ecological succession, which thus …mpacts the global vegetation distribution. Fire transforms some regions into bare ground,…and grasses…rassland starts to quickly dominate as they grow…hose landscapes because grass grows faster than trees. For shrubs and deciduous trees in the mid-stages of ecological succession, we found…here were no large differences in the overall coverage ratios between simulations including …hat included vegetation dynamics and those that did not. Simulations that did not consider vegetation dynamics showed a fire-induced global increase in NEP; however, a fire-induced decrease in NEP was found…etected in some regions in BGC-DV. We also found a…runs. A carbon sink reduction was also detected in regions where the dominant PFT changed from broadleaf and needleleaf evergreen trees to grasses…rass. While carbon emissions due to fire…rom fires were partly negated by increased terrestrial carbon sinks (NEP) in BGConly runs, they were enhanced by the reduction in

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

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

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

Code and Data Availability

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

Author Contributions

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

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삭제됨: for
삭제됨: marked
삭제됨: impacts
삭제됨: Interestingly, however
삭제됨: compared to non-burned
삭제됨: despite that fact that
삭제됨: assists in gaining an
삭제됨: fire
삭제됨: limited simulated potential
삭제됨: . Furthermore,
삭제됨: potential
삭제됨: found to be
삭제됨: noted
삭제됨: fire
삭제됨: fire
삭제됨: fire impact.
삭제됨: are dependent
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Conflict of Interest

The authors declare that they have no conflicts of interest.

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삭제됨: Van

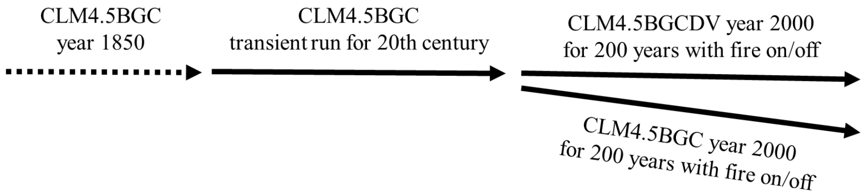

Figure 1: Flowchart showing model simulations conducted to investigate the interactive impact of fires and ecological succession on the Earth system using Community Land Model (CLM4.5) simulations extended with biogeochemistry (CLM4.5BGC) and BGC with dynamic vegetation (CLM4.5BGCDV).

삭제됨: fire

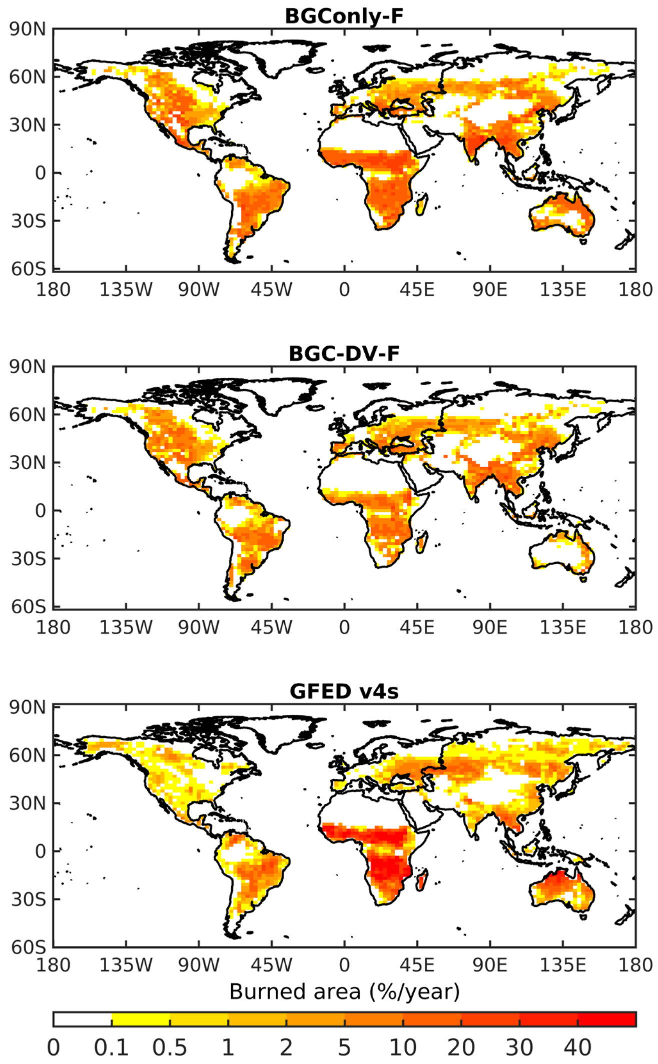

Figure 2: Annual burned area percentage by grid cell for CLM4.5BGC with fire (BGConly-F), CLM4.5BGCDV with fire (BGC-DV-F), and Global Fire Emission Database version 4 with small fires (GFED4s)

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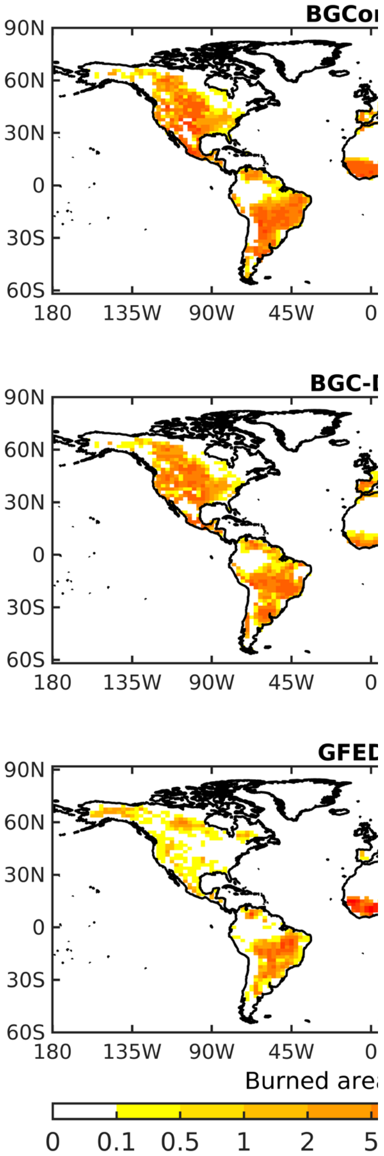
삭제됨:



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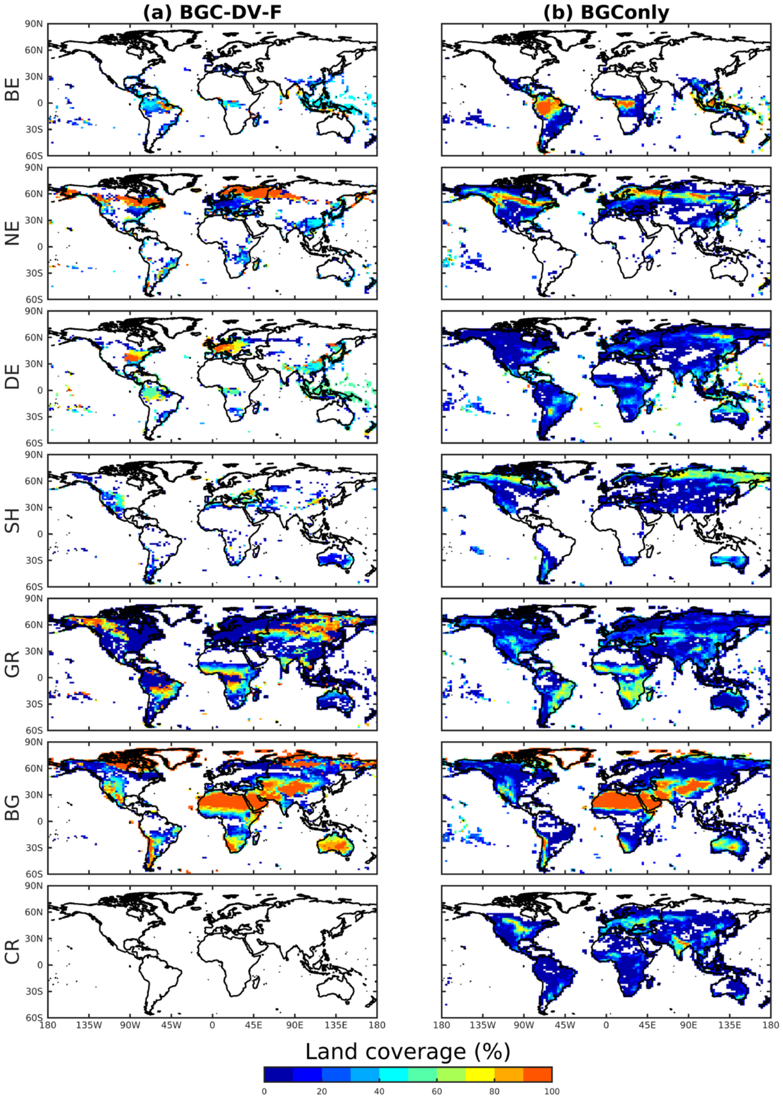
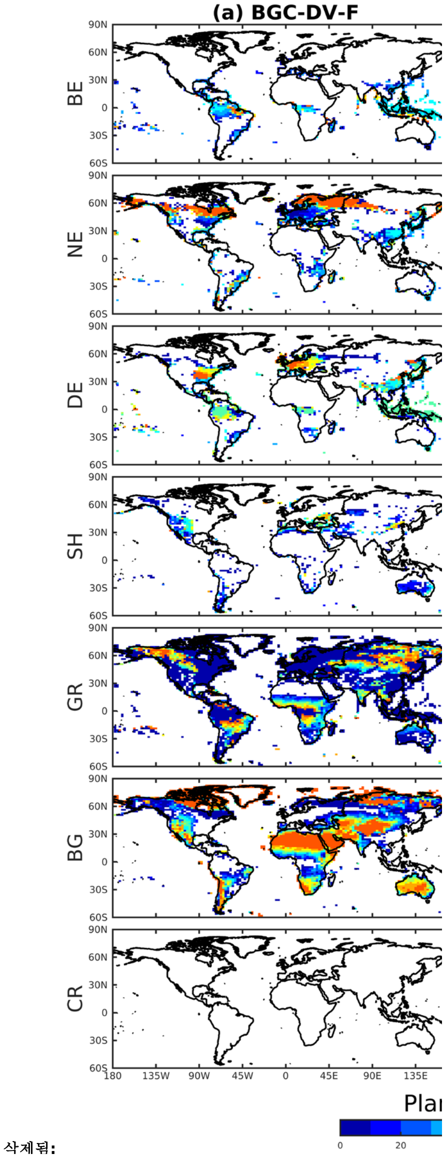


Figure 3: Percentages of land cover type (broadleaf evergreen (BE)), needleleaf evergreen (NE), deciduous (DE), shrub (SH), grass (GR), bare ground (BG) and crop (CR)) in BGC-DV-F and BGConly (the same for both BGConly-F and BGConly-NF).



삭제됨:

삭제됨:

삭제됨: bare ground (BE), grass (GR), shrub (SH), deciduous (DE),

삭제됨: broadleaf evergreen (BE

삭제됨: .

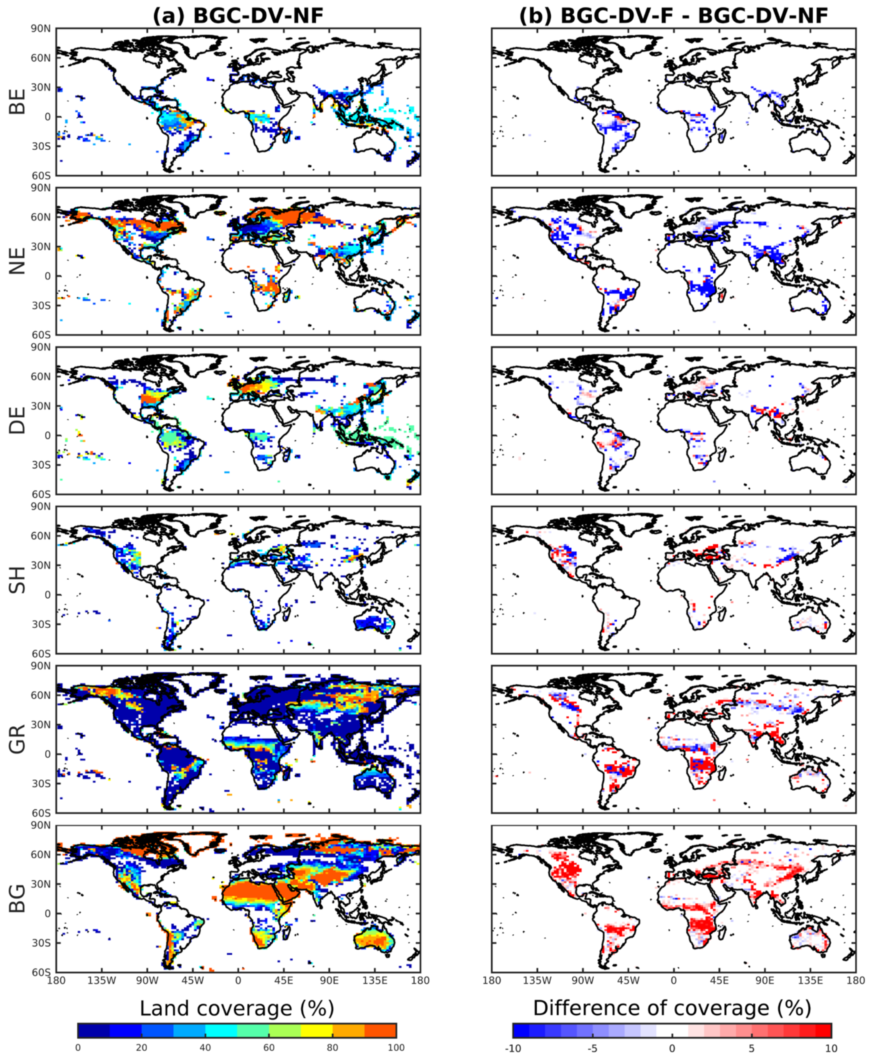


Figure 4: Percentages of land cover (broadleaf evergreen (BE), needleleaf evergreen (NE), deciduous (DE), shrub (SH), grass (GR), and bare ground (BG)) in BGC-DV-NF and differences in plant cover between BGC-DV-F and BGC-DV-NF.

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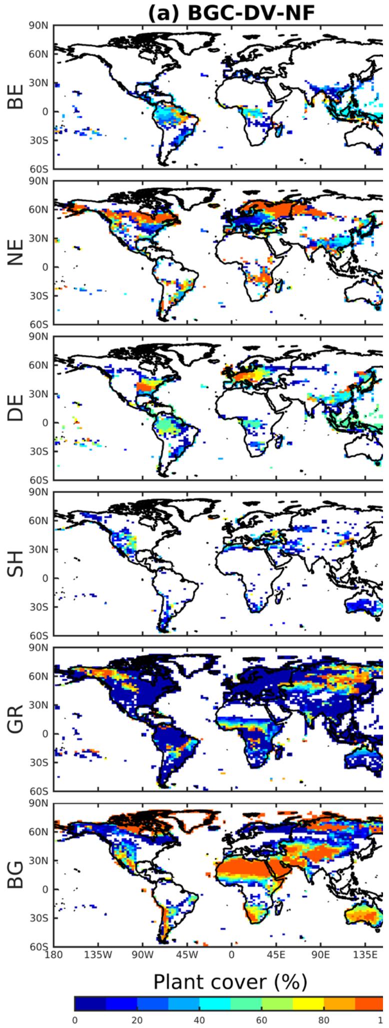


삭제됨: type (bare ground (BE), grass (GR), shrub (SH), deciduous (DE),

삭제됨: and broadleaf evergreen (BE

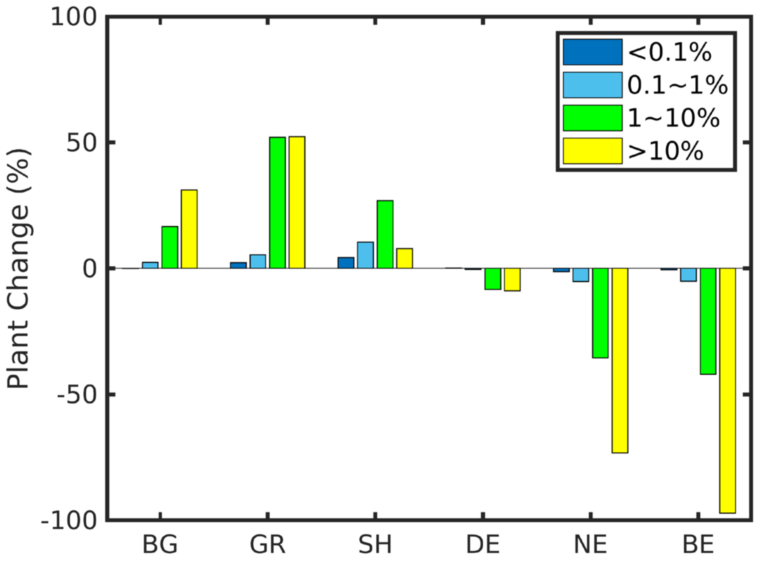


Figure 5: Differences in vegetation distribution (bare ground (BG), grass (GR), shrub (SH), deciduous (DE), broadleaf evergreen (BE), and needleleaf evergreen (NE)) ratios between BGC-DV-F and BGC-DV-NF for four burned area categories: under 0.1%, 0.1–1%, 1–10%, and greater than 10%.

삭제됨: Changes

삭제됨: ratios

삭제됨: ~

삭제됨: ~

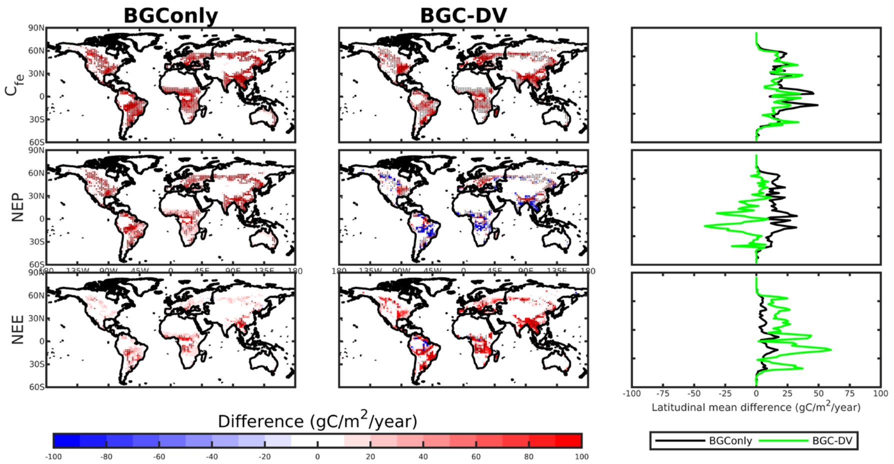
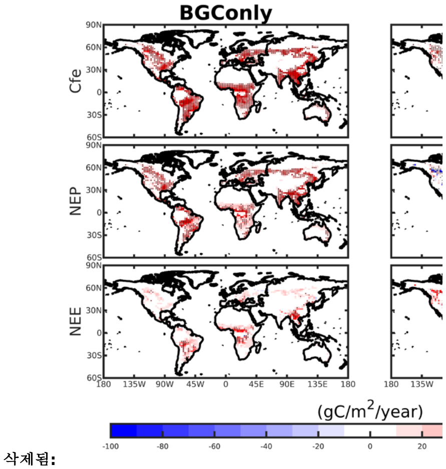


Figure 6: Differences in carbon emissions (C_{fe}), net ecosystem production (NEP), and net ecosystem exchange (NEE) caused by fires in BGConly (BGConly-F minus BGConly-NF; left column) and BGC-DV (BGC-DV-F minus BGC-DV-NF; middle column). Hashed areas indicate that the difference passed the Student's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



삭제됨:

삭제됨: ecological

삭제됨: due to fire between BGC and BGC-DV.

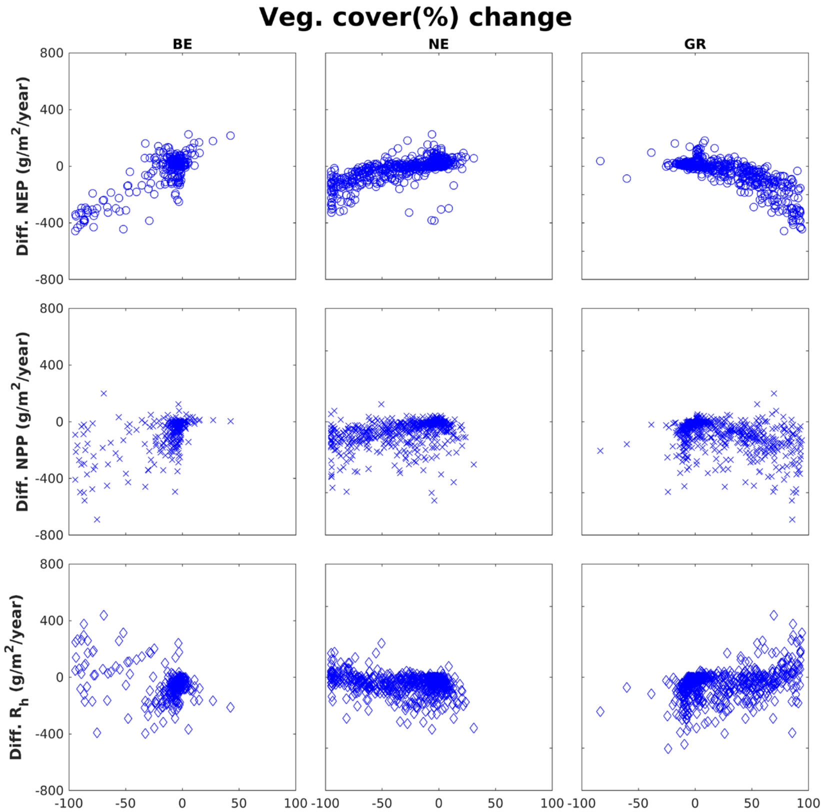


Figure 7: Differences in net ecosystem production (NEP), net primary productivity (NPP), and heterotrophic respiration (Rh)) due to fires in BGC-DV (i.e., BGC-DV-F minus BGC-DV-NF) according to percent changes in broadleaf evergreen (BE), needleleaf evergreen (NE), and grass (GR) vegetation types.

삭제됨: Response of differences (BGC-DV-F minus BGC-DV-NF) in

삭제됨: ,

삭제됨: , and R_h to percentage

삭제됨: bare ground

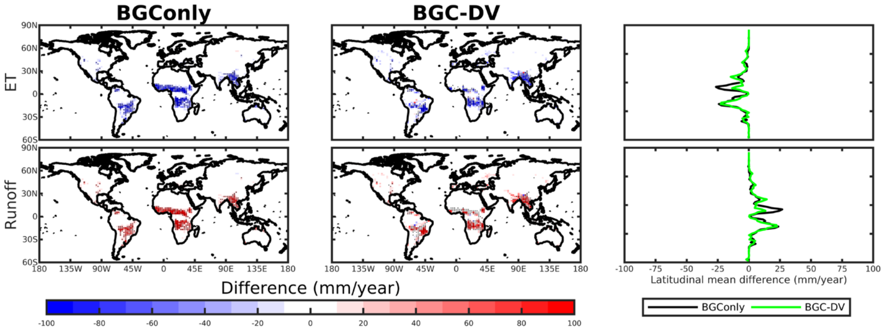
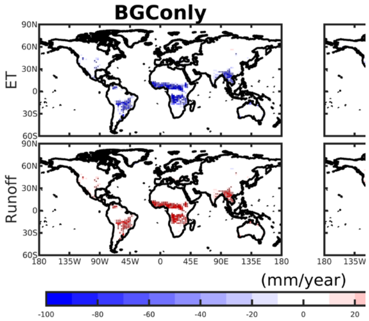


Figure 8: Differences in evapotranspiration (ET) and runoff due to fire in BGConly (BGConly-F minus BGConly-NF; left column) and BGC-DV (BGC-DV-F minus BGC-DV-NF; middle column). Hashed areas indicate that the difference passed the Student's t-test at the 0.05 significance level. Latitudinal mean differences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



삭제됨:
Figure 8: Same as Figure 6 but for water fluxes (evapotranspiration (ET) and runoff)

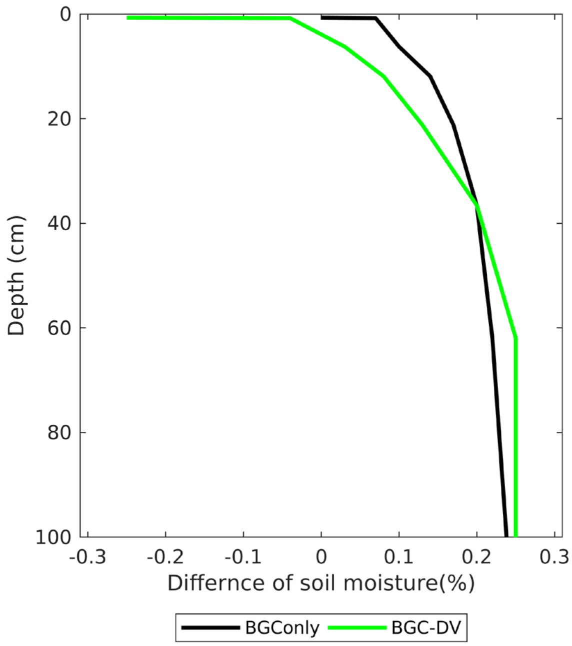


Figure 9: Difference in soil moisture (%) due to fire in BGConly (i.e., BGConly-F minus BGConly-NF) and BGC-DV (i.e., BGC-DV-F minus BGC-DV-NF).

삭제됨: **simulations.**

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)

삭제됨: four

삭제됨: .

삭제됨: Dynamic

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삭제됨: Model option

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삭제됨: model

삭제됨: ON

삽입한 셀

삭제됨: -DV-F

삭제됨: BGConly-F

삭제됨: ON

삽입한 셀

[1] 이동함(삽입)

삭제됨: OFF

삭제됨: BGC-DV-NF

삭제됨: .

Table 2: Percentage (%) land cover types (bare ground, grass, shrub, deciduous, needleleaf evergreen, and broadleaf 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	-	-

Table 3: Annual means of carbon budget for GPP, NPP, Ra, R_h, NEP, NEE, and C_{fe} and their differences between one with 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 (*) index indicates that the difference passed the Student's t test at the α = 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*

삭제됨: (Fire on- Fire off)

삭제됨: simulations

삭제됨: in Fire on and Fire off simulations

삭제됨: student's

삭제됨: Fire off

삭제됨: Fire on

삭제됨: Fire off

삭제됨: Diff

삭제됨: Fire on

삭제됨: Diff

Table 4: Pearson correlation coefficients between carbon fluxes (NEP, NPP, R_h) 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_h	-0.36	-0.17	-0.01	-0.13	0.27	-0.30

삭제됨: Correlation

Table 5: Annual mean water budgets for ground evaporation (GE), canopy evaporation (CE), canopy transpiration (CE), evapotranspiration (ET), and total runoff (RO) and the difference 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) in 10^3 km^3 yr^{-1}. Asterisk (*) index indicates that the difference passed the Student's t test at the α = 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*

삭제됨: Same as Table 3, but for the

삭제됨: of

삭제됨: in 103 km^3 yr^{-1}

삭제됨: Fire on

삭제됨: Fire off

삭제됨: Diff

삭제됨: Fire on

삭제됨: Fire off

삭제됨: Diff

Table 6 Annual mean values for LAI ($m^2\ m^{-2}$) and vegetation height (m) and the difference 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). Asterisk (*) index indicates that the difference passed the Student's t test at the α = 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*

삭제됨: **Table 6:** Same as Table 3, but for in LAI (m^2/m^2) and vegetation height(m).

삭제됨: Fire on

삭제됨: Fire off

삭제됨: Fire on

삭제됨: Fire off

삭제됨: Diff

삭제됨: Diff

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 α = 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*

삭제됨: **Same as Table 3, but for**

삭제됨: **in**

삭제됨: Fire off

삭제됨: Fire on

삭제됨: Fire off

삭제됨: Diff

삭제됨: Fire on

삭제됨: Diff