Reviewer #3:

This study projected future wildfire activities in Siberia by implementing a process-based fire module into a dynamic vegetation model. The main conclusion was that fire emissions continued to increase due to climate change. The authors also quantified the negative impacts of fire activity on tree mortality and NPP. While the topic of the study well fit the scope of BG, I found the presentation was very poor and many results were contradicting. I suggested a major revision but with strong doubts about the credibility of the model and the projections.

> **Response:**
>
> Thank you for taking the time to review our manuscript. We appreciate your acknowledgment that the topic of our study aligns well with the scope of Biogeosciences (BG). Your feedback regarding the presentation and clarity of our results is noted, and we apologize for any confusion or inconsistencies encountered.
>
> We understand the importance of ensuring the credibility of our model and projections. Your comments have raised valid concerns in this regard, and we are committed to addressing them through a major revision of the manuscript. We will carefully reevaluate our methodology, results, and interpretations to ensure accuracy and coherence throughout the manuscript. Moreover, we will provide additional clarification and justification for our findings to mitigate any perceived contradictions. We recognize the significance of transparently communicating our research outcomes to facilitate a better understanding among readers.
>
> Your feedback is invaluable to us, and we are grateful for the opportunity to improve our manuscript with your guidance. We assure you of our willingness to make necessary adjustments to enhance the credibility and quality of our work.
>
> Thank you once again for your thorough review and constructive comments.

1. First, the model descriptions were unclear. The authors put most of details, including equations and descriptions, to the supplementary material. However, the key processes should be listed in the main text for clarity. Most important, the links between the fire module and vegetation model should be explicitly explained. For example, what parameters did the SEIB-DGVM provide for SPITFIRE, and how the fire activity affect the vegetation distribution and ecosystem productivity. Such information determines which variables to be validated against observations.

> **Response:**
>
> We briefly describe the details of the model in section "2.2. Improved model principles" that include basic fire disturbance equation and emission estimation. We wrote the

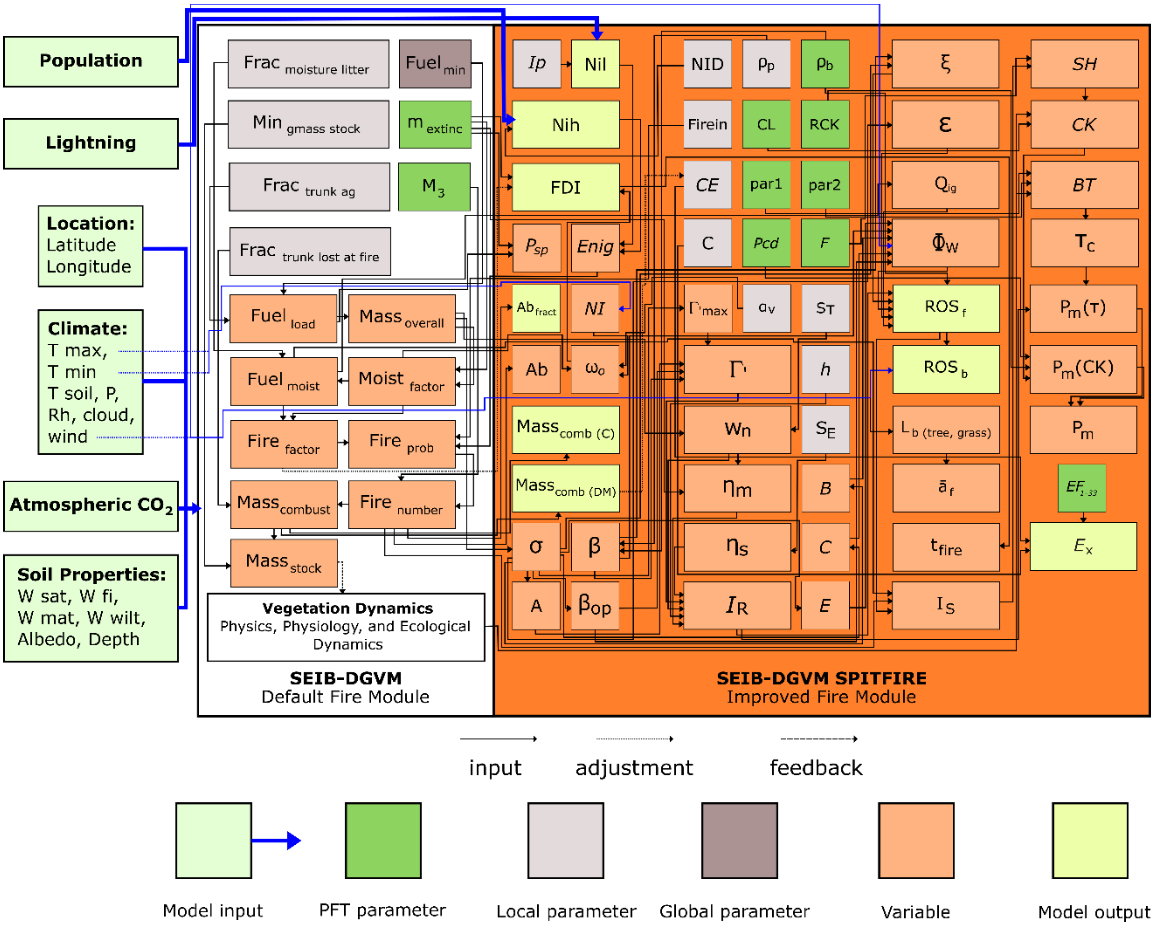
details of other variable calculations in the supplementary file because our model development only combines two existing models (SEIB-DGVM with SPITFIRE module), which have been described in detail by their respective authors (Sato et al., 2007; Thonicke et al., 2010).

The explanations we wrote in the equations are adjustments made in the integration process, and additional development processes we carried out, such as increasing the annual timestep to monthly timestep, and adding calculations of 33 burned biomass emissions.

a) We understand that we have not explained about fire-vegetation relationships in this section, and we appreciate for your suggestions. We have added the information about fire-vegetation relationships in this section (2.2), as follows:

   "The fraction of individual trees killed by a fire depends on PFT fire resistance (M3, Table 1). All grass leaf biomass, all dead and living tree leaf biomass, half of the dead tree trunk biomass, and half of the litter pool are released into the atmosphere as CO_2 during a fire, while the dead tree's residual biomass is converted into litter. In reaction to fire, all deciduous PFTs convert their phenology phase to dormancy, and if the stock resource of grass PFTs (gmassstock) does not meet the minimal value (50 g DM m^{-2}) following fire, the deficit is supplemented from litter (Sato et al., 2007). Furthermore, related to the fire-vegetation relationships, for herbaceous PFTs, both below-ground and storage biomass are preserved after a wildfire and used for the recovery of above-ground biomass. During this recovery period, herbaceous PFTs work on producing above-ground biomass while reducing their storage biomass, thus increasing the allocation ratio to above-ground biomass in the post-fire phase. For woody PFTs, fire only gives the option for individual trees to either die or survive. The surviving trees only lose their foliage biomass. As the foliage is lost, fine root biomass becomes unnecessary, leading to its rapid loss due to its fast turnover rate. In the spring following a fire, surviving trees convert storage resources into foliage and fine root biomass. The new net primary production (NPP) from the newly formed foliage first prioritizes the recovery of leaves and fine roots. Therefore, fires increase the allocation ratio to the foliage and fine roots in surviving woody plants."

b) Regarding the integration of parameters and variables in SEIB-DGVM for the SPITFIRE module, we determined three main variables that must be validated, namely fire variables (burned fraction, burned area, dry matter emission: GFED4s and GFED4), Aboveground biomass (ESA Biomass CCI), and CO_2 emissions (GFED4s, and GBEI). The determination is based on the relationship between fire, vegetation and emissions resulting from the interaction of these two variables.
   We considered to replace the current figure 2 with the complete improvement scheme, to give more information about the improvement and the integration between SEIB-DGVM and SPITFIRE module. The new Figure 2, as follow:


Population
Lightning
Location: Latitude Longitude
Climate: T max, T min T soil, P, Rh, cloud, wind
Atmospheric CO2
Soil Properties: W sat, W fi, W mat, W wilt, Albedo, Depth
Frac moisture litter
Fuel min
Min gmass stock
m extinc
Frac trunk ag
M3
Frac trunk lost at fire
Fuel load
Mass overall
Fuel moist
Moist factor
Fire factor
Fire prob
Mass combust
Fire number
Mass stock
Vegetation Dynamics
Physics, Physiology, and Ecological Dynamics
SEIB-DGVM
Default Fire Module
Ip
Nil
Nih
FDI
Psp
Enig
Ab fract
NI
Ab
ωo
Mass comb (C)
Mass comb (DM)
σ
β
A
βop
NID
ρp
ρb
Firein
CL
RCK
CE
par1
par2
C
Pcd
F
Γ'max
αv
ST
Γ'
h
Wn
SE
ηm
B
ηs
C
IR
E
ξ
ε
Qig
ΦW
ROS f
ROS b
L b (tree, grass)
ā f
t fire
IS
SH
CK
BT
TC
Pm(τ)
Pm(CK)
Pm
EF i, 33
Ex
SEIB-DGVM SPITFIRE
Improved Fire Module
input
adjustment
feedback
Model input
PFT parameter
Local parameter
Global parameter
Variable
Model output

2. Second, the model validations were questionable. Normally, the validations come before the projections. However, this study put the validations of fire models in the section 3.7, far behind the future projections. Some of the validations were not necessary. For example, Figure S2 compared the input and output of lightning flash rate and population density, which were actually the input of fire models instead of the prediction. Some validations were not consistent between different presentations. For example, Figure S17a compared the simulated and observed dry matter. The model predictions showed poor performance by missing almost all the observed fire episodes. However, in Figure 8, the monthly validations of simulated dry matter showed perfect performance with almost the same magnitude (Figure 8a) and R2=1 (Figure 8b) against observations. These results were too good to be true and seemed not consistent with Figure S17. Furthermore, the perfect simulation of dry matter (Figure 8b) resulted in a poor prediction of CO2 emissions (Figure 9). Was such bias attributed only to the emission factors? Then why making such a great effort to develop the sophisticated fire module when the simplest parameters caused the largest biases? BTW, I do not believe the R2 >0.6 in Figure 9 given such a wide range of scattering points.

   Response:

   Thank you very much for your detailed comments. We answer this comment in the following points:

   a) Apologize for the incorrect writing structure, in the previous version of the manuscript, subsections 3.1-3.4 discussed the performance of the default model with the improved model. We will move section 3.7 Improved model validation to the first section (3.1) in the adjusted manuscript.
   b) Our opinion, Figure S2 is quite important for us, because in our model development process (integration of SEIB-DGVM with SPITFIRE module), the ignition factor is the first variable that we integrate and differentiate with the previous fire module (Globfirm). Figure S2 shows one of the verification processes, that the model is able to read the input (after modification) and is able to process and produce input with exactly the same data as the given input (population density and lightning flash rate variables).
   However, it's just one of the improvement processes, that's why we decided to just put those images in the supplementary.
   c) Figure S17 is the Monthly Dry Matter Emission data comparison between GFED4s and SEIB-DGVM SPITFIRE, describing the dynamics of GFED4s data and the simulation results produced by SEIB-DGVM SPITFIRE. We explain this in L397, and the paragraphs that follow. This has been briefly explained at L412: the model is not yet able to reproduce the exact value at a specific time of year or month because the model is run in a longterm phase and is not yet able to predict sudden natural and anthropogenic conditions/ factors (model limitation).
   Meanwhile Figure 8 is Monthly Average Dry Matter Emission seasonality data comparison of GFED4s and SEIB-DGVM SPITFIRE (1997-2016). The results of this comparison correctly show the value of R2 = 0.99 (L415). This is an advantage of the model, where the model is able to learn data patterns over a long period of time with a high level of accuracy, because there is a calibration process carried out between the

model variables and the variables from the benchmark data used, as well as the integration between these variables in the model (Figure S11).

d) We apologize for not making it clearer in sub-section 2.4. related to the validation of the model output with some benchmark data that we did two types of comparison: numerical comparison and spatial comparison, and we did not explain the comparison in the manuscript (only in the figure label).

Figure 8b shows the Monthly Dry Matter Emission data comparison between GFED4s and SEIB-DGVM SPITFIRE (1997-2016) in plot form. This comparison is done by comparing the monthly extracted data of each dataset in a period of 20 years from 1997-2016.

Figure 9 is the CO_2 emissions spatial average comparison of SEIB-DGVM SPITFIRE module product with GFED4s and GBEI.

To clarify the information, we have corrected **L432** (This section only describes the internal model calculation process between dry matter emissions and gaseous emissions produced by SEIB-DGVM SPITFIRE.) and the sentence after it as follows:

"When comparing the annual average dry matter emission data and CO_2 emissions generated by the model, the results correlated perfectly (100%, Figure S27), indicating that the model runs well according to Equation (3) and the projected CO_2 and other emissions have the same distribution patterns as the dry matter variable, because all of the emissions calculation are based on the dry emission variable. However, they differ in their values because each emission species has a different emission factor."

And we adjusted the sentence in **L436** to clarify the validation process, as follows:

"Spatially, the annual average CO_2 emission model data were 63% (Figure 9.a) and 67% (Figure 9.b) correlated with the GFED4s and GBEI data, respectively."

The difference in spatial distribution of model-generated variables with GFED4s data have been explained in **L508.** The comparison results are different due to differences in the data being compared, numerically extracted data and spatial data. We will write about this in a separate subsection "Model uncertainty", which explains that the model is able to simulate very well numerically with all benchmarks data because we have a calibration process for each variable with benchmark data over a long period of time. The limitations of the current model are that it is not able to simulate sudden fluctuations due to natural factors that have not been considered in the simulation process, and the distribution pattern of emission data depends on the distribution pattern of the simulated fire variables. Thus, the fire ignition calculation and its process are very important that will affect the following variables: emissions.

Related to the R2 score of the Figure 9, we have shared the dataset in the Google Spreadsheet, please access through the following URL:

https://docs.google.com/spreadsheets/d/1RkgB8qGQaLAKI4EkeUHZTS0S8L3bq4y8/edit?usp=sharing&ouid=114559960745563618149&rtpof=true&sd=true

3. Third, the future projections were doubtful. This study used daily meteorology from four RCP scenarios output by MirocAR5. How to reduce the uncertainties from a single climate model projection? Normally, these scenarios showed very different tendencies of warming, indicating different fire probability. However, the projections of fire activities showed very similar results among these scenarios (e.g., Figure 4, Figure S5, Figure 12 …). Does it mean that the future wildfire activity in Siberia will increase at the similar rate no matter how warm the climate becomes? Furthermore, the updated fire module showed good correlations between burned fraction and burned biomass (Figure S11d), suggesting tight connections between these two parameters. The burned fraction is projected to increase continuously after the year 2040 (Figure S5b). Then why burned biomass showed such a large fluctuation over the same period?

Response:

Thank you very much for your detailed comments. We answer this comment in the following points:

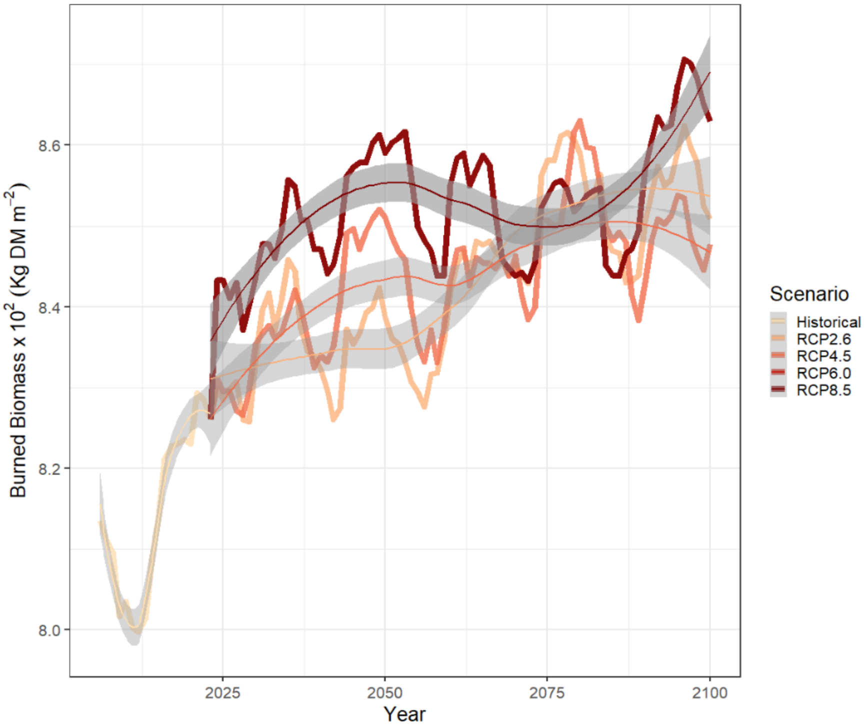
a) We use the MirocAR5 dataset as is, regardless of its uncertainty. The model data bias has been corrected using "EWEMBI" observational dataset. (https://www.isimip.org/gettingstarted/input-data-bias-adjustment/details/21/)

b) The fire projection results that do not have much difference between under all different RCP scenarios (e.g., Figure 4, Figure S5, Figure 12...), we suspect based on the calculation process flow, because the fire calculation does not directly use/consider the temperature variable. Instead, the fire variable is estimated based on the calculation of a chain of variables ranging from fuel availability fuel load (litter + aboveground biomass), moisture content, ignition factors (lightning and population), parameters accompanying the calculation of these variables (such as the minimum fuel load threshold of 200 g C m^{-2}: Sato et al., 2007), and also this is affected by the type of input dataset used and the limitations of the model.

   However, the estimation results produced by the model have been validated with several benchmark data which include the fire itself, vegetation and emissions variables (Table 3).

c) Yes, the correlation of burned fraction and burned biomass variables in the improved model (Figure S11.d) shows the correct relationship, where the increase of burned fraction, the burned biomass also increases.

   The burned biomass variable has an increasing trend as well (same as burned fraction) from year to year as shown in the following figure:



Related to the fluctuation is normal, because there is a process of vegetation dynamics (tree death due to fire, and vegetation succession process after forest fires, and phenological factors simulated in this SEIB-DGVM). Thus, there is no contradiction from these variables.

4. Finally, the quality of result presentations was low. For example, the figures were very similar among the subplots of Figure 4e-4h, Figure, Figure S4e-S4h, Figure S6. Such information is useless as the readers could not tell their differences. Figure S28 showed the projected fire emissions of 33 trace gases by putting all the subplots together without any summary. It's difficult to tell their differences and the main conclusions. The authors also spent great efforts in comparing results from the default and updated fire modules (e.g., Figures S4, S5, S9, S10, S11). While it's important to understand how different the fire predictions before and after the improvement of fire modules, the authors could show some key results (e.g., Figure S11) and put more efforts in the validations of the updated model against observations, not only for fire activities but also some ecosystem parameters (e.g., tree height, biomass, NPP).

Response:

Thank you very much for your detailed comments. We answer this comment in the following points:

a) We have combined the images of each visualized variable. We present one map to show the distribution pattern (representing all estimates from other RCP scenarios as they are spatially similar), as follows:

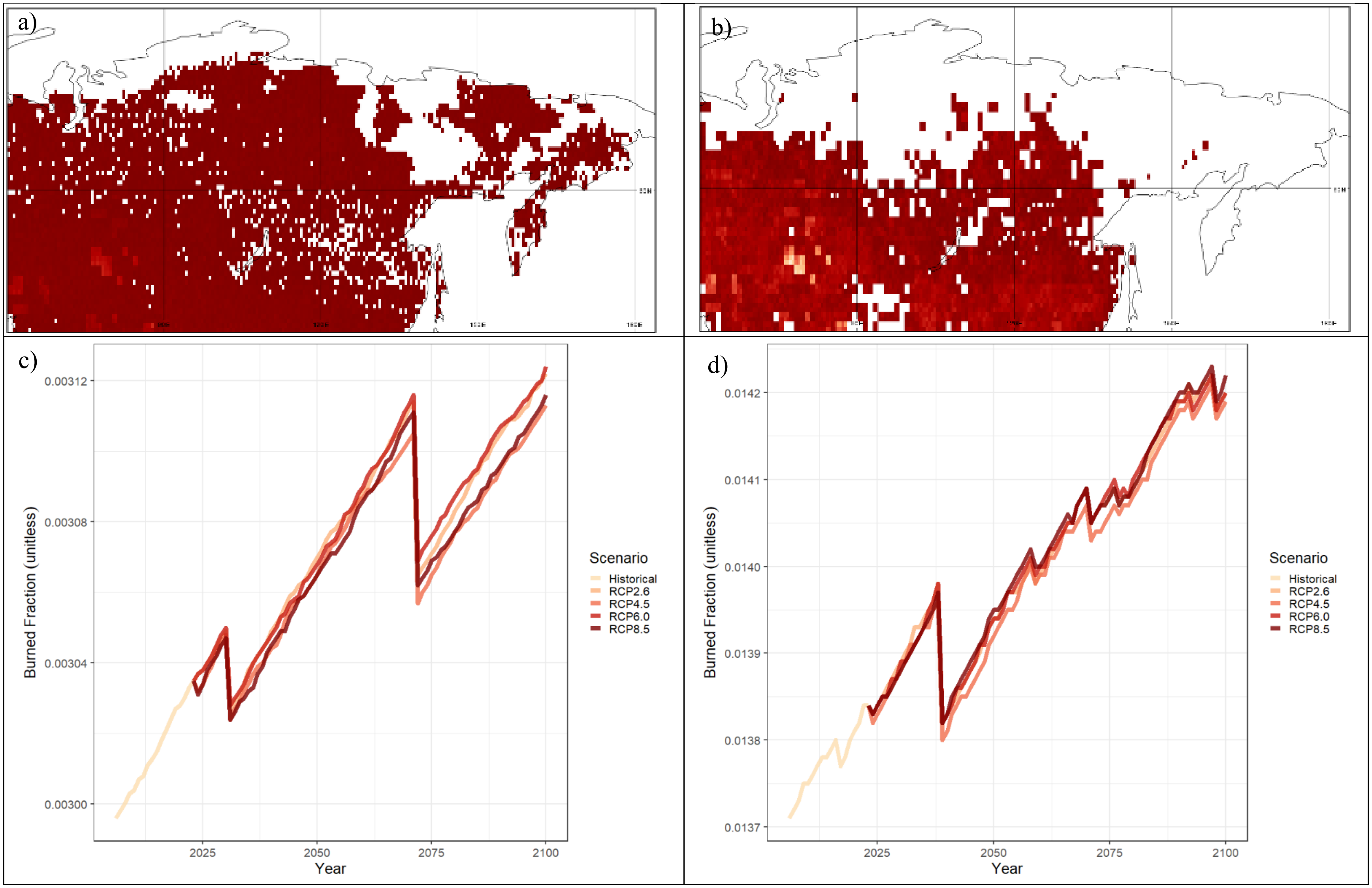


Figure S4. Distribution pattern map and graph of annual average burned fraction (2006-2100). Default SEIB-DGVM (a and c), SEIB-DGVM SPITFIRE (b and d).

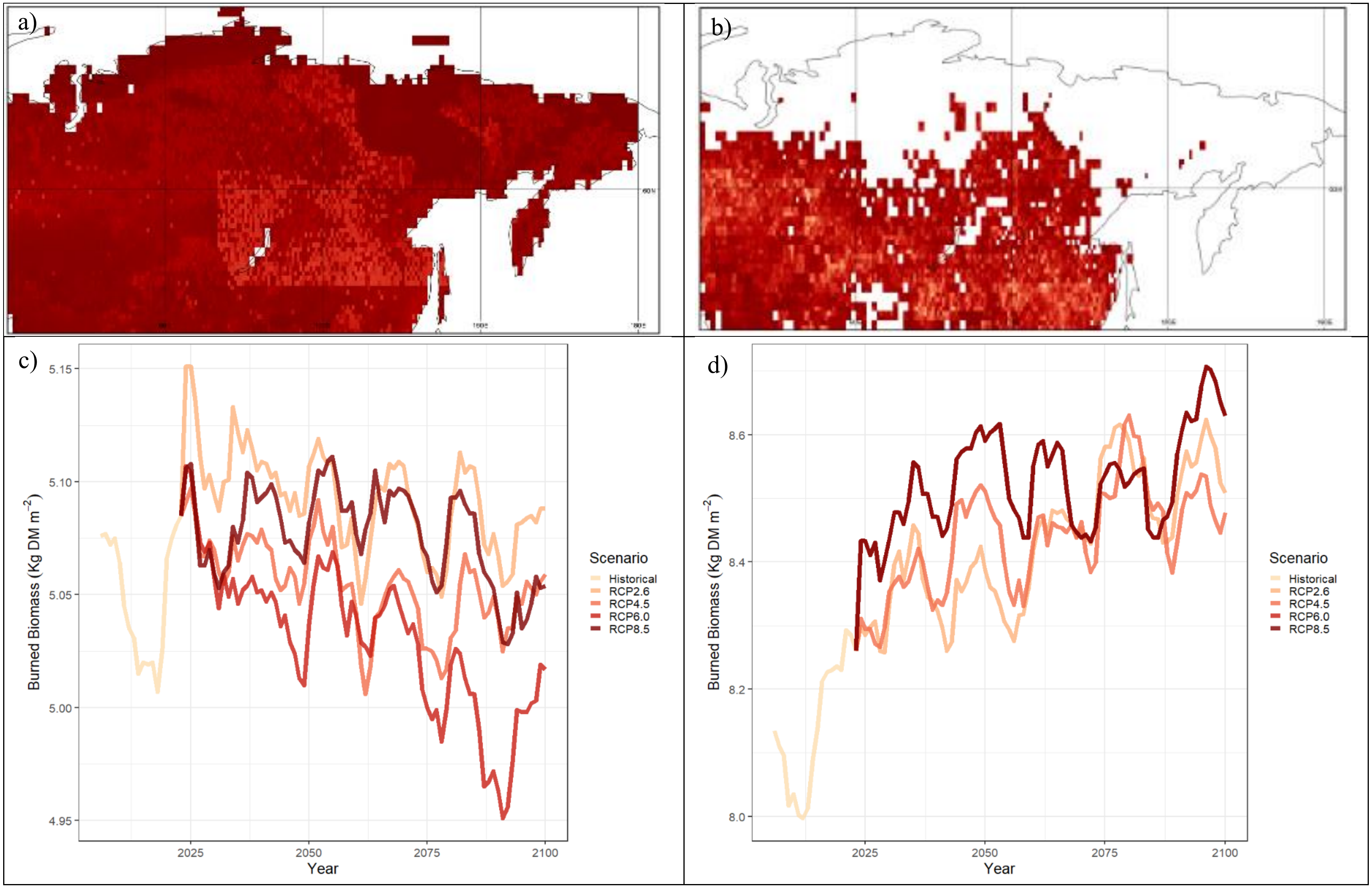


Figure 4. Distribution pattern map and graph of annual average burned biomass (2006-2100). Default SEIB-DGVM (a and c), SEIB-DGVM SPITFIRE (b and d).

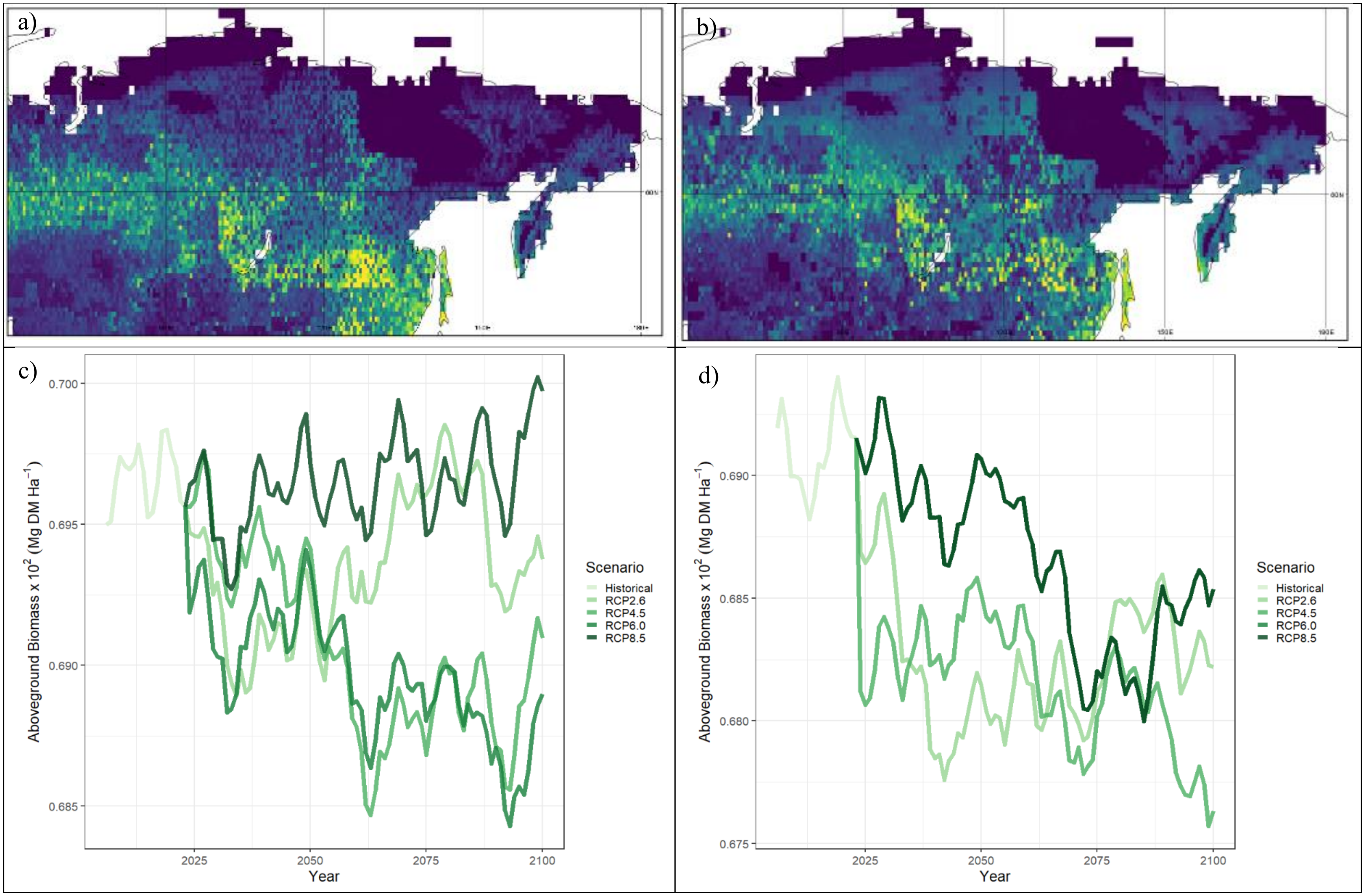


Figure 5. Distribution pattern map and graph of annual average aboveground biomass (2006-2100). Default SEIB-DGVM (a and c), SEIB-DGVM SPITFIRE (b and d).

b) Thank you very much for the suggestion, we have added these few sentences in the **L590** to explain Figure S28.
"Spatially, the projections depict heterogeneous patterns of burned biomass emissions, with regions of high emissions intensity concentrated in areas of larch forest (Larix spp.), consistent with Figure 1 and our simulation results, where the fire and emission variables show high values in central to southern Siberia (Figure S4.b, Figure 4.b, and Figure S6.b). This is reinforced by field-based estimation data, that fires in this region result in high tree mortality 76%, Siberian larch forests experience greater aboveground carbon loss after fire than do North American forests, both in absolute and relative levels (Webb et al., 2024). We also visualized all the 33 graphs depicting projected burned biomass emissions, offering valuable insights into the future dynamics of the burned biomass emissions in Siberia. Across these graphs, we observe distinct temporal patterns, revealing trends in burned biomass emissions over time. Under the RCP8.5 to RCP2.6 scenarios, overall emissions by 2100 are projected to increase by 2.6 %, 1.9 %, 1.05 % and 1.04 % compared to 2000 emissions (Figure S28), and the twenty-year dynamics are summarized in Table 4 and Table S4."

c) We present Figures S4, S5, S9, S10, S11 because they are needed to show the differences in simulated fire variables, vegetation, and the relationship between the improved model and the default model. This is not our main purpose, but only to strengthen the explanation given, so we only include it in the Supplement. Regarding the explanation of the figure, it has been explained in detail in the main text, respectively.

Regarding the validation of the model with benchmark data, we have explained in section 2.4, and the validation results are in section 3.7. Improved model validation.

We agree with your suggestion that we should not only discuss fire activity, but also ecosystem parameters. In the manuscript, we have explained about the NPP projection and comparison with some other observational data **(L548).** We have also added the NBP variable (in section 4.2) to the revised manuscript in accordance with other reviewers' suggestions to strengthen the discussion related to the strength of carbon flux caused by disturbance: fire.

Figures

Figure 10: What's the meaning of the shadings in (a)? What's the meaning of the points in (b)?

Response:

a) The shading in Figure 10.a is the ± standard deviation of $PM_{2.5}$ emissions projected by each RCP scenario.

b) The points in Figure 10.b are comparisons between the model's $PM_{2.5}$ emission projections with Copernicus Atmosphere Monitoring Service (CAMS) (Romanov et al., 2022) data in seven Russian territories during 2004-2021.

Figure S5: What's the reason for the sharp decline of burned fraction around 2035 in (b)?

Response:

We suggest this is due to the high fire fraction in 2038 (which has a similar value in the 2060 projection), resulting in high carbon emissions in that year and beyond. This is evidenced by the low NBP values in 2021-2040 compared to the average of the other years in Figure rev1, and on a point scale, the NBP variables projected by all RCP scenarios have negative values, indicating a carbon source (Figure S35).

Discussion related to NBP (rev1 and rev2 drawings) has been added in sub section 4.2. adjusted according to other co-author's suggestions as well.

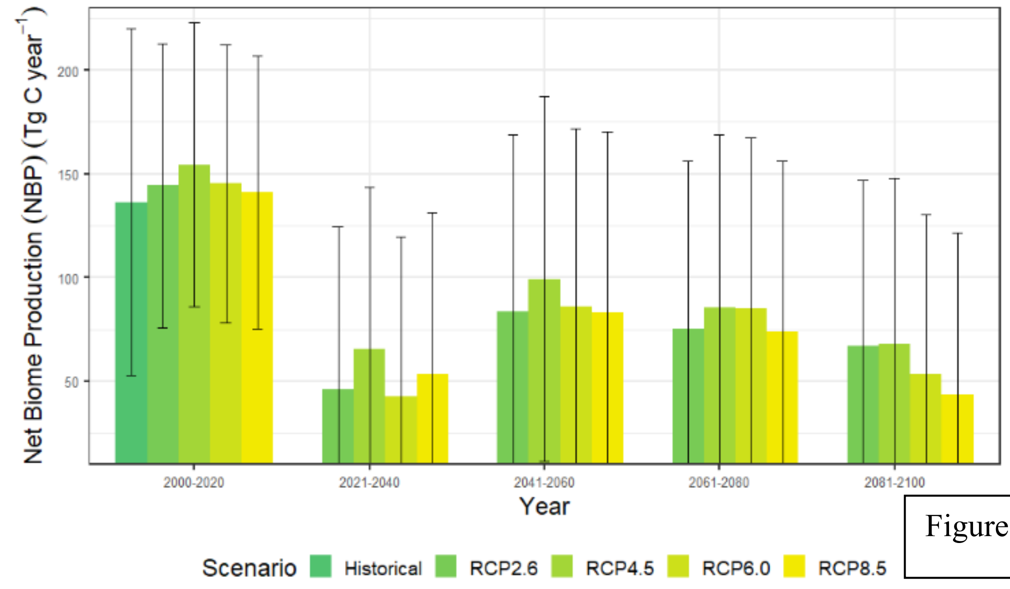


Figure S34.

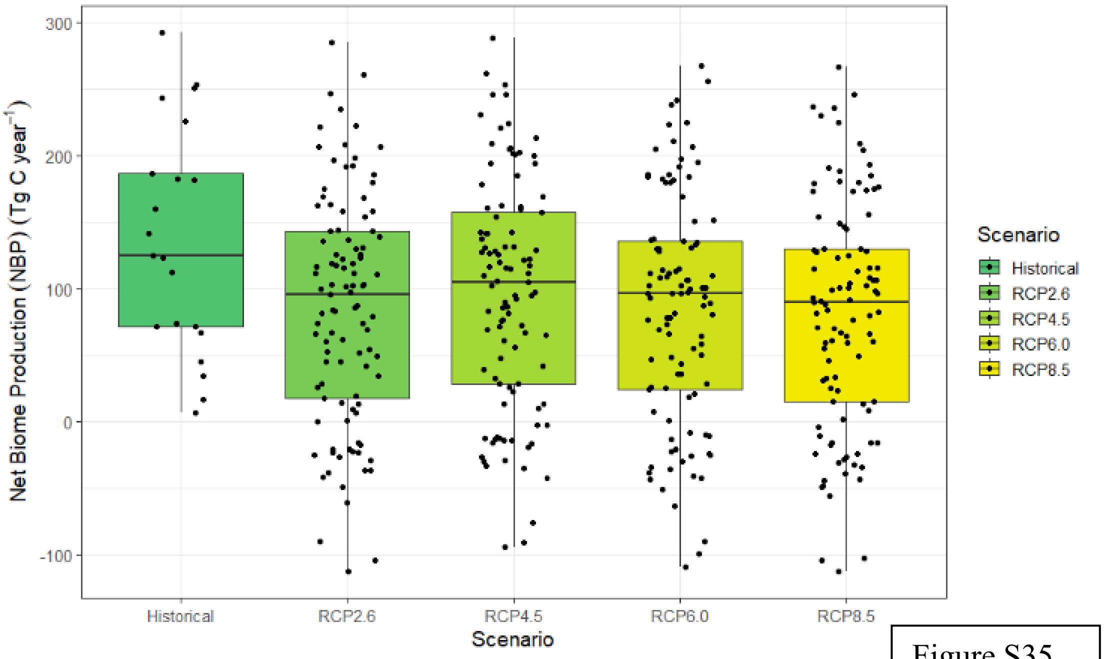

Net Biome Production (NBP) (Tg C year^{-1})
300
200
100
0
-100
Historical
RCP2.6
RCP4.5
RCP6.0
RCP8.5
Scenario
Scenario
Historical
RCP2.6
RCP4.5
RCP6.0
RCP8.5

Figure S35.