

Responses to the reviewer comments for manuscript egusphere-2025-804 (Global wildfire patterns and drivers under climate change).

In each section, the reviewer comments are shown in **black**, followed by our responses in **blue**, and newly added text in the manuscript is shown in **bold blue**.

We have received feedback from two out of three reviewers. Unfortunately, one reviewer has not responded despite multiple requests. The reviewers' assessments are contrasting. While both reviewers acknowledge the manuscript's improvement, one is satisfied with the modifications, while the other has more concerns.

I agree that the manuscript has improved significantly since the first submission and is well-written. However, I also agree with Reviewer 2 that further analysis is needed, particularly regarding the idea that a sensitivity analysis of the model runs can help to better understand the role of the different drivers than the machine learning itself. The analysis with the machine learning is interesting in my opinion, but should be expanded to the GFED BA data to understand if CLM can reproduce the relationship between drivers and BA. I see two possible solutions, the first is to run the sensitivity analysis, and the second to apply (for current climate) the machine learning approach to both the model and GFED (see below more details) After carefully reading the manuscript and reviews, I suggest a substantial revision. Below are some additional comments.

We thank the Editor for this constructive summary and for recognizing the significant improvements since the first submission. We have carefully considered the suggestions regarding the additional analysis, particularly the second option, running GFED-based machine-learning comparison. However, sensitivity model experiments could not be conducted within our current capacity. Besides this, we have implemented a substantial revision addressing all other comments, clarifying the methodology, enhancing burned area validation, restructuring the discussion and conclusions, and improving figure clarity and overall readability.

We have explicitly acknowledged the need for sensitivity experiments with changing population and land use in Section 4 (Discussion) and its scientific importance (see, “Attribution experiments,” under the Discussion). We have also clarified how future studies could extend our framework to perform such analyses.

Section 4: Discussion

“... Similarly, population growth and urbanization may lead to more frequent human ignitions or enhanced suppression capacity, depending on regional context. ... Future research would benefit from targeted sensitivity simulations that systematically vary climate drivers (e.g., CO₂, temperature, precipitation) or land use parameters, either independently or in combination. ...”

Line 54: Add a reference for this statement from GFED5.

Reference added:

“However, BA trends largely vary with region, where the boreal region experiences an increasing trend ($2.5\% \text{ yr}^{-1}$), while most other regions show reductions by up to $2.7\% \text{ yr}^{-1}$ (**Chen et al., 2023a**).”

Line 118: "of key carbonaceous species to provide": Please clarify which species.

Revised the sentence to list the specific species included in our analysis.

“... of key carbonaceous species – **total carbon (TC), black carbon (BC), organic carbon (OC), and carbon monoxide (CO)** – to provide ...”

Line 130: It is unclear why the authors did not conduct a test involving changes in land cover according to available land use change scenarios. This should be clarified. Validate the model against burned area. I suggest moving the validation to the results section.

We thank the reviewer for this helpful suggestion. We have clarified in the manuscript that land use and population were intentionally held constant to isolate climate-induced fire responses. Including transient land-use change scenarios would have introduced additional socioeconomic effects and confounded the attribution to climate alone. This rationale is already explained in last paragraph of Introduction, Methods (Section 2.3) and further discussed as a study limitation in Section 4 (Discussion, Attribution experiments).

Introduction:

“... By focusing on SSP1/SSP3 climate-driven changes while holding socioeconomic drivers (land use and populations) constant, our study isolates the effects of warming on fire dynamics, offering a clearer understanding of how different climate pathways shape future wildfire risks. ...”

Section 2.3:

“... These experiments were aimed to assess the isolated impacts of climate change on wildfires and emissions of air pollutants, while holding anthropogenic land management constant.”

Section 4:

“Attribution experiments: Our study isolates the climate effect by holding anthropogenic influence (changes in land use and population density) constant. While this provides a controlled framework for evaluating climate-driven wildfire risks, real-world fire dynamics are shaped by a broader set of factors. Future land use changes – such as agricultural expansion, forest fragmentation, or

abandonment – can alter fuel continuity and flammability. For instance, fragmentation may reduce fire spread by breaking fuel connectivity, while deforestation or abandonment could increase fire risk by creating more open, combustible landscapes. ...”

In addition, following the reviewer’s suggestion, we have moved the model validation of burned area and fire emissions from the Methods to the Results section (now Section 3.1) to improve logical flow.

“3. Results

3.1 Validation of global burned area and fire emissions”

Lines 225–227: Why don't the authors report immediately the average BA calculated over the same time period? This value is reported below, and I would move it up. For the recent time period, it seems that the CLM substantially underestimates the BA (3.9 vs. 5.2 million km²). Therefore, I would not call them aligned, but rather, I would try to explain the differences. The authors attempt to demonstrate regional differences below, but a more in-depth discussion of this bias and the significant seasonal variations (Figure 1) would be beneficial to readers.

The CLM5-simulated global burned area for 2015–2024 is 5.18 ± 0.37 million km², not 3.9 million km², as may have been misread. To avoid this confusion, we have also revised the statement and briefly discussed possible reasons for CLM slightly underestimation compared to GFED5 as:

“Our results also align with **satellite-based** estimates for 2001–2018, **which report an average global BA of 4.63 million km² and a range of 3.9 to 5.2 million km²** (Lizundia-Loiola et al., 2020). Despite some biases, the model performance is robust, with a normalized mean bias of +15.6% (–29.1%) and a correlation coefficient (R) of 0.64 (0.62) when compared to GFED4.1 (GFED5). **The underestimation relative to GFED5 likely rises arises from CLM coarse resolution, fixed land-use configuration, and limited representation of small fires (Hantson et al., 2020; Chen et al., 2023a).**”

Section 2.5: I agree with Reviewer 2 that a sensitivity analysis can be less “black box”, however I see value in the analysis of the authors. My suggestion is to run the same analysis on GFED as they did on the model. This would allow us to determine whether the model and GFED “observations” share the same climate and vegetation drivers. Variables such as aboveground biomass, climate reanalysis, and surface soil moisture can be used as predictors of GFED biomass (BA) for the current climate period.

We agree that applying the same machine-learning framework to GFED burned-area data would provide additional insights into model–observation consistency. We have conducted this test and explained both in methodology and results section as:

Section 2.4 Machine learning models

“To evaluate the realism of CLM5 fire drivers, we conducted a parallel analysis using GFED5 observed burned area (2007-2020) (Chen et al., 2023b) and ERA5-Land reanalysis data (Muñoz Sabater, 2019). The observational analysis used the same seven predictors, with leaf area index (LAI) serving as a proxy for vegetation carbon and top layer soil moisture (0-7 cm) serving equivalent to 10-cm CLM5 soil moisture. Both global and high latitudes domains were analyzed. Notably, the high latitude GFED5 dataset exhibits extreme zero-inflation, with only 5% of spatiotemporal observations containing non-zero burned area during JJA, contributing to lower predictive performance ($R^2 = 0.23$) compared to the global analysis ($R^2 = 0.58$). This data limitation reflects the inherent challenge of predicting fire occurrence in observation-sparse boreal regions.”

Section 3.4

“Comparison with GFED5 observations reveals fundamental challenges in comparing fire drivers across different spatial domains and data sources. The driver importance itself varies dramatically within GFED5 – precipitation dominates globally (23.6%) but ranks fifth in high latitude regions (13.0%), CWA and windspeed gain importance at high latitudes (Figure S11). While CLM5 shows strong high latitude fire predictability ($R^2=0.70$), GFED5 low predictive skill ($R^2=0.23$) indicates environmental variables alone poorly explain observational high latitude fires, mainly due to zero-inflation noted in Section 2.4. Despite this, both CLM5 and GFED5 consistently identify moisture variables as top drivers, validating CLM5 representation of water limitation as a key boreal fire constraint after biofuel availability.”

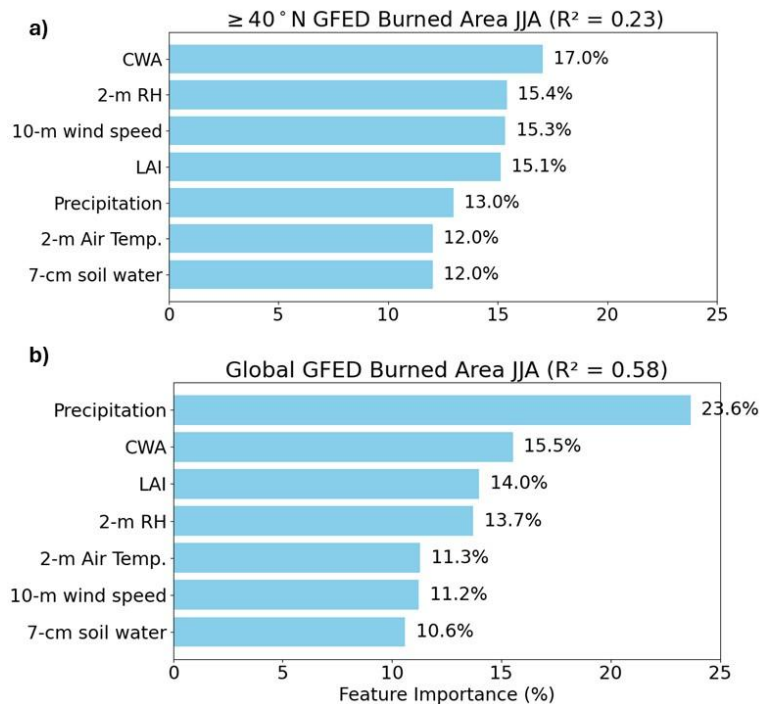


Figure S1. Feature importance of environmental drivers of GFED5 wildfire activity during 2007 to 2020 boreal summer (JJA) over (a) northern latitude ($\geq 40^\circ \text{N}$) and (b) global using XGBoost machine learning model.

Line 512: The statement is correct, considering the CLM model structure. However, considering the model structure, the role of biomass itself can be overestimated, while the fine biomass (deadwood, understory, and fine flammable material) is one of the main drivers, as determined by data analysis. This is also encapsulated in the intermediate fire productivity hypothesis. Analyzing the drivers using GFED can also help determine if the role of total biomass is overestimated in the current analysis.

We agree that CLM may overemphasize the influence of total biomass while underrepresenting the role of fine and dead fuels that primarily control fire spread. To address this point, we have added following statement in Section 3.4:

“... CLM5 tracks multiple vegetation carbon pools, including fine roots and dead biomass (Lawrence et al., 2019). However, the fire module uses an aggregated fuel load for ignition and spread, without differentiating the structure of fine and dead fuels, which may overemphasize the influence of total biomass in controlling fire behavior.”

I suggest splitting the discussion and conclusions.

We have separated the final section into two: Section 4 “Discussion” and Section 5 “Conclusions,”.

References:

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- Lawrence, D. M., Fisher, R. A., Koven, C. D., Oleson, K. W., Swenson, S. C., Bonan, G., . . . Zeng, X. B.: The Community Land Model Version 5: Description of New Features, Benchmarking, and Impact of Forcing Uncertainty, *J. Adv. Model. Earth Syst.*, 11, 4245-4287, 10.1029/2018ms001583, 2019.
- Lizundia-Loiola, J., Otón, G., Ramo, R., and Chuvieco, E.: A spatio-temporal active-fire clustering approach for global burned area mapping at 250 m from MODIS data, *Remote Sens. Environ.*, 236, 10.1016/j.rse.2019.111493, 2020.
- Muñoz Sabater, J.: ERA5-Land monthly averaged data from 1950 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). [dataset], 10.24381/cds.68d2bb30 (Accessed on 18-10-2025), 2019.