Reply to main comments (original reviewer comment presented in bold)

This is a detailed and extensive piece of work that attempts to use HDI to improve the JULES-INFERNO fire model.

I'm considered to be a SME and I'm somewhat confused by the approach. It is not clear why the authors have taken this approach, primarily because so many critical factors in wildfire propagation are not included. By taking a global data set, 'de-weathering', the assumption seems to be that the remaining correlation is between GFED and HDI, which patently isn't the case.

Although INFERNO necessarily requires a simplification of the complex fire processes, my concern is that the approach taken here does not include processes that are a critical part of the system.

I'm not a statistician, but the work largely neglects the physical process driving fire behaviour. I wonder if an EOF analysis would be more appropriate.

The study shows a 'de-weathered burnt area fraction'. It is unclear to me what the physical meaning of this metric is and how can it sensibly be interpreted with context to current fire regimes and understanding of fire weather and fire behaviour. I would be surprised if the meaning is clear to other readers.

The processes driving fire activity globally are extremely complex and the various contributing factors are not fully acknowledged in the study or incorporated into the approach. A primary driver of fire is fuel availability and there is significant uncertainty in future fuel regimes (including fuel structure, dryness and landscape continuity) in a changing climate. Shifting hydrological regimes influencing fuel availability are a factor driving global fire activity in recent years. The focus in this paper seems disproportionately towards HDI and imbalanced with the other ingredients in fire regimes.

This is a very detailed and methodical study, but the statistical approach does not reconcile with the physical process that drive global fire activity, which are highly heterogeneous. The approach assumes that by 'de-weathering' the GFED dataset the remaining fire mapping is dependent on HDI.

We thank the reviewer for the detailed review and thoughtful comments.

The simplifications in INFERNO reflect the necessary design choice for global-scale fire modelling within Earth System Models (ESMs), where spatial resolution and computational constraints restrict explicit representation of local-scale physical fire processes such as topographic effects, fine-scale fuel heterogeneity, or detailed fire spread dynamics.

In general, global fire models (e.g., SPITFIRE, LPJ-GUESS-SPITFIRE, CLM-fire, and INFERNO) represent fire behaviour through parameterized relationships that link fire occurrence, spread, and emissions to key environmental drivers, primarily climate, vegetation (fuel type and load), and human activity. This approach enables large-scale consistency and interaction with biogeochemical cycles, which is essential for coupled ESM applications. While such models cannot resolve local fire dynamics, they successfully capture first-order global patterns of fire activity and response to climate and human influence, making them valuable tools for understanding fire–climate–carbon feedback at regional to global scales.

Regarding the deweathering method, this approach is used to remove the influence of climate-driven weather variability from the burned area data. The intent is to isolate one dominant fire driver (e.g., socio-economic factors) from the remaining influences, facilitating analysis of their effect on fire activity. We do not assume that the residual variability after deweathering is solely due to socio-economic factors; other drivers, including fuel availability, topography, and local management practices, may also contribute. This is explicitly noted in the revised manuscript to avoid overinterpretation of the residuals.

Together, INFERNO and the deweathering approach provide a framework for examining broad-scale patterns and trends, while acknowledging that fine-scale, local fire processes and heterogeneity are not fully resolved.

<u>Specific comments.</u>

- **Fig 3 shows the 'log transform 'deweathered' burnt area fraction % (of global fire emissions database)', (which is derived from satellite hot spot data and >12 years old). It is unclear how this should best be interpreted in context of fire regimes, or future emissions scenarios.**

We thank the reviewer for this comment. A log-transformation is applied to 'deweathered' burnt area fraction to meet the assumptions of linear regression and to improve the interpretability of the results. The burnt area fraction exhibited a right-skewed distribution, and log-transforming them reduced skewness and stabilized variance, helping to satisfy the assumptions of normality and homoscedasticity. In addition, because the logarithm is defined only for positive values, the transformation also ensured that all data points used in the analysis were non-negative.

To clarify the intent of this analysis, we note that this approach shows that the deweathered burnt area fraction declines with increasing HDI, with a mean slope of approximately –6.57 (%), based on the assumption of linearity. On this basis, we might expect future changes in HDI to influence fire emissions, in addition to changes in climate and other factors such as fuel load. We include this clarification here for completeness but do not intend to add these sentences to the revised manuscript.

- **GFED isn't explained in the text (it is in the appendix, but it's key to the main study and the Giglio study is from 2013, so a relatively old dataset (The Giglio reference date is 2013, but Figure 7 states 1997-2016). Giglio's paper shows a map with GFED regions; these are very heterogeneous (just one example is that Mediterranean Europe and Greenland are treated as homogeneous in the current study, while there are great differences in HDI and fire regimes across that spatial area).**

We thank the reviewer for these helpful comments. We commit to clarifying the description of the Global Fire Emissions Database (GFED) in the main text to ensure that its role in this study is clearly understood. GFED is a long-running, operationally updated dataset used globally for fire and emissions research. While the core methodological reference (Giglio et al., 2013) describes the development of the GFED4 framework, the dataset itself has been continuously updated to include fire emissions up to recent years (including 1997–2016 in our analysis). It is common practice in global environmental monitoring to cite the key methodological paper for such datasets even when newer data releases extend beyond the publication year.

Regarding the aggregation of GFED regions, we agree that they are spatially heterogeneous, and we note this as a limitation of using regionally averaged data in a global modelling framework. The focus of our analysis is on broad-scale relationships and trends between human development, climate, and fire activity, rather than capturing fine-scale spatial variability in fire regimes. We will add text to the revised manuscript to emphasize this point and to clarify how GFED data were used in the study.

- **The Canadian FWI has been used. The FWI is intended for use in forested areas of Canada. It was not designed to be used in Eurasia, tropical areas, grasslands or agricultural areas, rainforest vegetation or peat fuel. It captures short and medium term fuel drying. It does not**

capture seasonal grass growth or long-term drought. As it was intended to capture fuel availability in forest types, FWI does not readily translate to fuel availability across other landscapes, particularly on climate time scales.

The Canadian Fire Weather Index (FWI) is a component of the Canadian Forest Fire Danger Rating System (CFFDRS) and provides a numerical rating of fire intensity based solely on weather conditions (temperature, relative humidity, wind speed, and precipitation). Although it was originally developed for Canadian boreal forest conditions, the FWI system is not region-specific and has been successfully applied in diverse ecosystems worldwide, including in Europe, South America, Australia, and parts of Africa and Asia. Its broad adoption stems from its simplicity, weather-based formulation, and scalability.

- **The FWI is applied here globally outside it's intended aim. The calculation method (average time period used) is not explained clearly in the text. From Figure 1 it is unclear if this is averaged over all seasons and all years. Averaging at high latitudes will mask any extremes, which are typically the times when impactful fires occur.**

We thank the reviewer for this helpful comment and for pointing out the lack of clarity. In relation to the use of FWI, we have addressed this in response to the previous comment. To provide more clarity, Figure 1 presents the spatial distribution of the Fire Weather Index (FWI) over all seasons and years for the period 1997 to 2016 – as a climatology and trend - intended to illustrate the global pattern and long-term trend in fire-conducive conditions rather than to represent seasonal or interannual extremes. This averaged map is only used to provide contextual information on the broad-scale variability of FWI across regions.

However, for all the more in-depth analyses presented in this work, the monthly FWI is used, not the long-term average. The use of monthly data preserves important temporal variability and enables a more detailed assessment of fire–climate relationships, including those relevant to high-latitude regions where extremes are important. We will revise the figure caption and methods section to explicitly state this distinction and clarify the calculation procedure to avoid misunderstanding.

- **HDI is averaged 1997-2016. This time period may not be is appropriate as input to projections (China for example is changing rapidly). HDI values are applied over large areas (countries) with heterogeneous land use and population density, which is inconsistent with typical fire regimes, which can vary considerable over relatively small areas, particularly with topographic and vegetation structure and noting that topography is not included in the framework.**

Thank you for this comment, clearly indicating that the manuscript was not entirely clear. As indicated above, Figure 1 is solely used to provide contextual information on the broad-scale variability of different variables, including the Human Development Index (HDI) across regions, and their trends over the period 1996 to 2017.

However, for the remaining analyses in the manuscript, the HDI data were not averaged over 1997–2016. Instead, we used an annual HDI dataset, which provides year-by-year values at the national level. These annual HDI values were supplied as inputs to the JULES-INFERNO+HDI framework and were used directly in the analysis without temporal averaging. We agree that HDI represents country-scale socioeconomic conditions and does not capture subnational heterogeneity in population density, land use, or topography. However, our goal was to assess the influence of large-scale human development trends on fire activity, consistent with the global scope of the model. Incorporating finer-scale socioeconomic and topographic variability is an important avenue for future work as higher-resolution datasets become available.

We will revise the Figure 1 caption and the corresponding text to explicitly state this distinction between the purpose of Figure 1 and the subsequent analysis, so that the temporal frequency and the time period of the data used is more explicitly stated, thus providing more clarity and avoiding any misunderstanding.

- **My understanding is that an objective of the modelling is to capture emissions, but there is no distinction made between low intensity and high intensity fires, in either the GFED4 data or**

FWI, or whether the fire is an agricultural fire or wildfire (which will have varying fuel consumption and therefore produce varying emissions), the seasonal timing of the fire activity, or the vertical extent of the fire, which are important considerations for emissions. For emissions, it is typically the large intense fires that are critically important as these are the ones which produce upper-troposphere and stratospheric injection of particulates and are often associated with incomplete combustion. Although INFERNO necessarily requires a simplification of the complex fire processes, my concern is that the approach taken here does not include processes that are a critical part of the system.

We thank the reviewer for highlighting these important points regarding fire intensity and emissions processes. We acknowledge that INFERNO represents a simplified framework and does not explicitly distinguish between low- and high-intensity fires, agricultural versus wildfires, or the vertical injection of emissions. Similarly, the GFED4 data and the Fire Weather Index (FWI) inputs provide aggregate fire activity information rather than detailed characterization of combustion completeness or plume injection height.

The rationale for this approach is that INFERNO is designed to capture broad-scale, integrated fire activity and associated emissions trends at global and regional scales, rather than reproducing individual fire behaviour at sub-grid or event-specific resolution. Consequently, the model is most effective at estimating relative changes in emissions driven by climate, weather, and human development factors, while absolute emissions from extreme, high-intensity fires may be underrepresented.

We note that the model outputs remain useful for trend analysis, scenario comparison, and large-scale atmospheric impact assessment, but agree that incorporating processes such as fire intensity, fuel type, seasonal timing, and vertical extent would be required for a more mechanistic representation of emission injection and atmospheric transport, and we commit to clearly identify this as an important direction for future work in a revised version of the manuscript.

- **Fuel availability is not considered. Fire processes are different in different landscapes and a global approach to describing fire regimes is problematic due to the variation in fuel type and fuel availability..**

We thank the reviewer for this comment. In INFERNO, fuel availability is represented through its coupling with the Joint UK Land Environment Simulator (JULES) land surface model, which simulates vegetation type, litter, and biomass carbon pools that determine the amount of combustible material within each grid cell. Although the model does not explicitly resolve fine-scale variations in fuel structure or composition, this approach allows fuel availability to vary dynamically with vegetation productivity and climate. We acknowledge that this represents a simplification of real-world fire processes and that differences in fuel type and landscape structure are not fully captured.

- **Fuel type and structure consumed is not discriminated, although this will be a significant factor in calculating emissions.**

We thank the reviewer for this valuable observation. In the INFERNO model, fuel availability is represented implicitly through the coupling with the JULES land surface model, which provides estimates of vegetation type, litter, and biomass carbon pools. These variables determine the potential fuel load available for combustion and thus influence fire occurrence and emissions. While INFERNO does not explicitly model fuel moisture or structural heterogeneity at sub-grid scales, this coupling enables the model to capture broad spatial and temporal variations in fuel availability consistent with the underlying vegetation dynamics and weather.

It is also worth noting that due to resolution and computational constraints, global fire modelling frameworks inevitably are required to simplify the diversity and complexity of fire processes across ecosystems, and that differences in fuel composition, structure, and continuity are not fully resolved at the model's spatial scale.

In addition, while other studies may use INFERNO for generating fire-related emissions, in this manuscript, the authors are solely investigating the potential use of the HDI in influencing fire activity and on the performance of the model in representing burned area fractions. In particular, this work does not include any analysis on the ability of INFERNO to represent fire emissions.

- **Fuel availability is a key factor in landscape fires. Fire trends can and do vary hugely with different vegetation structure (eg grasslands often burn annually). The consideration of vegetation type and structure and fuel availability is rather superficial in this study, however in many parts of the world, this is likely to be a key ingredient in changing fire-climate regimes.**

We thank the reviewer for these detailed observations. In INFERNO, vegetation type, litter, and biomass carbon pools from the JULES land surface model provide an implicit representation of fuel availability, allowing broad-scale variation in fire activity to reflect vegetation productivity and climate. This approach does not explicitly capture fine-scale fuel structure, fuel continuity, or landscape fragmentation, which can influence fire size and spread in specific regions.

- **Fuel continuity is a key factor influencing fire size. This can be (indirectly) related to HDI due to landscape features such as highways, railway lines, which often act as barriers to fire spread or can be used to support containment lines. Natural boundaries such as watercourses and topographic features can also constrain fire spread. Population density will also contribute to fragmentation of landscapes.**

We appreciate the reviewer's thoughtful observation. The primary focus of this study is to assess the influence of socio-economic factors (via HDI) on broad-scale fire activity, rather than to resolve sub-grid processes such as fuel continuity, natural or anthropogenic barriers, or topographic constraints. While we agree with the reviewer that these factors are important for local fire behaviour, global-scale models like INFERNO necessarily simplify these processes to maintain computational feasibility and large-scale consistency. We have clarified these limitations in the revised manuscript.

- **The term 'suppression', is used several times but is not clearly defined. Many landscape fires are not actively suppressed, or are only suppressed or contained in proximity to infrastructure and assets. Suppression and containment will vary considerably geographically and methods such as hand tools, backburning, fuel reduction will vary considerably dependent on resources, assets and fuel loads. Mitigation efforts such as planned burns and fuel management will also vary with HDI (and resources). In addition, many fires extinguish overnight, dependent on favourable weather conditions, fuel availability and fuel continuity, but these processes are not captured in the current study.**

We thank the reviewer for this commentt, and we commit to provide a better definition of suppression in the context of this work in the revised manuscript.

<u>Short comments</u>

- **The fire-science terminology could be used more precisely. Examples include 'fire models' and 'fire simulators'.**

In this context, we use the term fire model as a mathematical representation of a real-world system that simulates fire behaviour under different conditions. The term *"fire model"* is used consistently to describe approaches that estimate fire occurrence, spread, and emissions at large spatial and temporal scales. We agree that stating this will improve clarity and commit to include it in a revised version of the manuscript. Please note that the term *"simulator"* is only used as part of the name of the land surface model JULES (Joint UK Land Environment Simulator).

- **L40 A discussion on how the processes are included in CMIP frameworks would be useful**

We thank the reviewer for this comment and will include a brief description on how different CMIP models represent fire in a revised version of the manuscript.

- **L105 FWI is not the influence of climate**

To account for climate effects on fire activity without implying that FWI represents climate itself, we use the FWI as a weather-driven indicator of fire conditions. Specifically, we apply a linear regression of normalized burnt area against FWI to capture the component of fire activity attributable to short-term weather variations. The predicted effect of FWI from this regression is then subtracted from the normalized burnt area, producing a “deweathered” dataset in which the influence of daily weather variability is removed. This approach allows us to isolate and analyse the influence of socio-economic factors, such as HDI, on fire activity while controlling for climate-driven variability.

- **L140 topography is a key factor in fire spread as is local meteorology.**

We thank the reviewer for this important observation. In INFERNO, the burnt area calculation is decoupled from local meteorology and topography, as these processes are not typically resolved at the coarse spatial scales used in Earth System Models (ESMs). Instead, INFERNO relies on plant functional type (PFT)-specific flammability (including meteorological components) and fire occurrence metrics, including ignitions and average burnt area per fire, which capture broad-scale patterns of fire activity. While this approach does not explicitly represent topographic effects or fine-scale weather variability, it allows the model to simulate large-scale, climate- and vegetation-driven fire dynamics. We acknowledge this as a limitation and will better reflect this in a revised version of the manuscript noting that sub-grid heterogeneity in topography and local meteorology is not resolved, which may influence local fire spread.

- **L180 It is not clear to me how the 1860 -2016 dataset is applied**

We thank the reviewer for this comment. The JULES model was run from 1860 to allow for an appropriate spin-up period and to ensure that the model’s biogeophysical states (e.g., soil carbon pools, vegetation structure) reached equilibrium before the main analysis period. Running the model from this historical start date provides a physically consistent baseline for simulating subsequent changes.

In addition, a time series of HDI values was prescribed for each model grid cell throughout the simulation period. This allowed the model to represent spatial and temporal variations in human development over time and to evaluate how these changes interact with environmental drivers in shaping fire dynamics.

We provide this clarification here for completeness but do not propose to add these details to the revised manuscript.

- **L200 What are the origins of this approach for global vegetation structure, particularly its relevance to fire prone environments. 40% seems high for many trees. The vegetation types described aren’t reflective of many fire regimes.**

The origin of this approach is documented in Burton et al. (2019) and Burton et al. (2020), this work describes the methodology for including fire mortality in INFERNO and includes a comprehensive evaluation of the model performance in representing the evolution of vegetation within the context of JULES model. The mortality parameter is specified in Burton et al. (2019) and is derived from current literature. We thank the reviewer for the comment, and commit to clarifying this in a revised version of the manuscript.

- **L250 this could be due to fuel availability and continuity, but these factors haven't been included.**

We agree that fuel availability and continuity are important determinants of fire activity and may influence trends in burnt area (BA) after deweathering. In our analysis, we make the simplifying assumption that, once the influence of weather is removed, residual variations or trends in BA can be primarily attributed to socioeconomic factors, represented here by HDI. We then use the model simulations to test this assumption and to evaluate how including the HDI–BA relationship affects model performance.

We acknowledge that fuel availability and continuity can influence BA trends. These processes are represented in INFERNO via its coupling to the land surface scheme, however, they are not included in the empirical relationship used to derive the HDI dependence

- **How are large and small fire sizes categorised (0.2, 0.6 etc is not a fire size)**

We thank the reviewer for this comment. The values 0.2 and 0.6 refer to burnt area fractions, not individual fire sizes. These fractions represent the proportion of each grid cell that is burned, which we use to categorise “small” and “large” fire events in the analysis. We commit to make this clearer in a revised version of the manuscript.

- **Maps of the regions are not shown until the appendix and the regions are highly internally heterogeneous with regard to HDI and fire regimes.**

The regions used in our analysis are defined according to GFED4 (Giglio et al., 2013) and have been widely adopted in global fire studies. While we acknowledge that these regions are internally heterogeneous with respect to HDI and fire regimes, they provide a standardized framework for comparing fire activity and emissions at large spatial scales.

Given the widespread use of the GFED4 regions in previous studies, we respectfully suggest that this figure remains in the Appendix.

- **What is 'burnt area fraction' a fraction of? Giglio 2012 specifies this as the fraction of each grid cell that burns each year but that is not clear in the current study.**

We thank the reviewer for this comment and will ensure this is clearer in a revised version of the manuscript.

- **Fig 10. It is hard to compare these plots due to the varying y axes. The interannual variability seen in the observations is interesting, but is not well captured in the smoothed JuELS-INFERNO-HDI, which is a concern.**

The varying y axes are necessary to reflect the wide range of burnt area magnitudes across different fire regions, allowing each region’s variability to be visualized clearly. Regarding the interannual variability, this limitation is addressed in the manuscript (Section 4.2, lines 580–585), where we note that the incorporation of socio-economic factors in INFERNO via HDI reduces interannual variability for most regions. While this smoothing improves model performance in some regions (e.g., TENA and CEAM), it reduces the model’s ability to capture high variability in regions such as BONA, BOAS, AUST, CEAS, SHSA, and NHSA. Importantly, even the control model (JULES-INFERNO) with larger interannual variability still underperforms relative to observations in these regions.

- **There are many acronyms, some of which are not expanded (eg GFED4). Also several small typos.**

We thank the reviewer for this comment and will ensure this is addressed in a revised version of the manuscript.