Response to Reviewer 2

Manuscript:

Fire across frontiers: Satellite-based investigation of climate-fire interactions in West Asia

We sincerely thank Reviewer 2 for the thorough and constructive comments on the manuscript, and the encouragement for conducting this regional study. The detailed suggestions help us identify several areas where the clarity, writing, and presentation can be improved. We have further grouped the overall 71 comments into 7 thematic groups, including title and scope, figures and visualization, data documentation, spatial analysis, statistical tests, results and discussion framing. We address the comments in each group as illustrated below.

Group 1 — Title and overall scope

> *I am not convinced with the focus on 'satellite-based investigation' in the title. For example, the word 'satellite' does not appear even once in the Introduction. Since the authors have not done any direct analysis of satellite imagery, but used GIS products developed by other authors/agencies, I would suggest modifying the title to better reflect the content of the manuscript. For example, 'GIS-based investigation' could be an alternative.*
>
> *Similar to the previous comment, the authors have not focussed exclusively or primarily on climate factors, but to a broader set of variables. I would suggest modifying the title to better reflect their analysis.*
>
> ***Original title**: Fire across frontiers: Satellite-based investigation of climate-fire interactions in West Asia*

Author's response: We thank the reviewer for the suggestion on the current title, which overpromises in two aspects and might therefore mislead readers. First, we did not produce our own satellite datasets in this study we primarily used satellite-derived geospatial products. Furthermore, 'climate-fire interactions' suggests that climate is the primary analytical focus, but we actually examined a broad set of variables in this study.

In the revision, we will update the title to better reflect the actual scope of the analysis. Our current working suggestion is: **'Fires across frontiers: Spatiotemporal analysis of vegetation fire dynamics and drivers in the Middle East (West Asia)'**. This removes the 'satellite-based' framing, drops the 'climate-fire interactions', and replaces them with 'vegetation fire dynamics and drivers' that better reflects our multi-variable, descriptive-analytical approach.

Group 2 — Figures and visualisation

2.1 Figure 1: map features

> *Fig 1: Can latitudes and longitudes be superimposed on the map for reference, and for association with the text on Line 122.*
>
> *Line 128: Can the geographical references mentioned in the text be included in Fig 1 for readers unfamiliar with the region?*
>
> ***Original manuscript text (Line 128)**: The western part of the study area experiences a Mediterranean climate, receiving more than 400 mm of rainfall annually and over 1,000 mm in mountainous areas such as the Taurus, East Anatolian Mountains, the Zagros Mountains, Anti-Lebanon and the Caspian Sea region, supporting the fuel production of coniferous forests and dense shrublands that generate substantial fuel loads.*

> *Line 441: It will be helpful if the authors included a graphic map marking the Mediterranean zone, for example in Fig 1, since they reference it multiple times, and it would make it easier for the readers to follow their observations.*
>
> ***Original manuscript text (Line 441)****: Additionally, these countries possess the region's most extensive belts of Mediterranean shrublands and fertile croplands, which serve as primary fuel sources.*

Author's response: We thank the reviewer for these suggestions, which will make Figure 1 more useful for readers unfamiliar with the region. We will add latitude and longitude gridlines to Figure 1, directly linking the visual to the coordinate range stated on Line 122. We will also add labels for the key geographical features referenced in Line 128 (mountain ranges, wetlands, plains) and for the Mediterranean climate zone boundary.

2.2 Figures 2 and 3: y-axis and normalisation

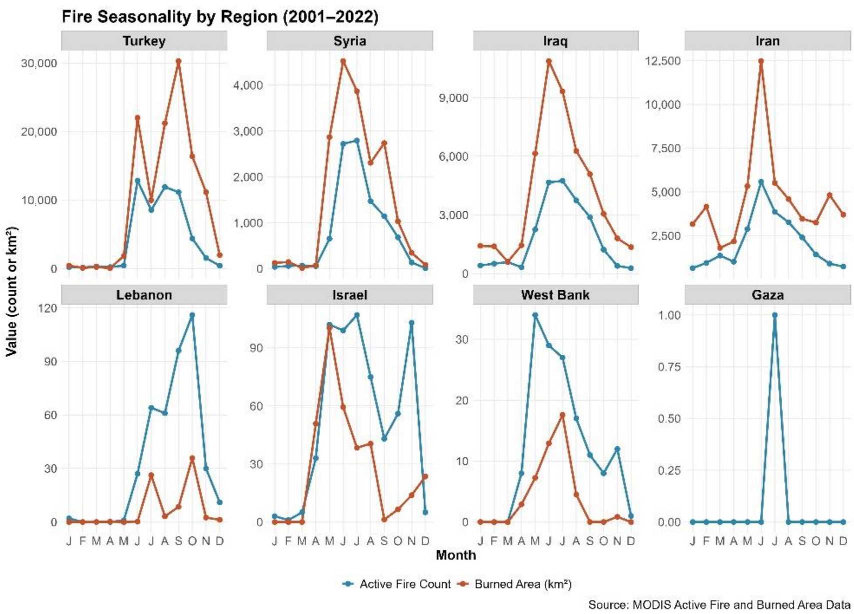
> *Figure 2: Can the authors elaborate on the y-axis? Is the normalisation of y-axis done over the entire country's area, over the grid cells of that type, or only over grid cells that have active fires? Same comment for Figure 3.*

Author's response: We appreciate this question and acknowledge the caption was not sufficiently clear. The normalisation is performed over the total country area. We calculated it using the AF count or BA for each land cover class, divided by the total area of the respective country in km². We will add this explicitly to the figure captions for Figures 2 and 3 to avoid ambiguity. We will also clarify in the Methods (Section 2.3.1, Line 228) what 'comparable fractions' refers to, which addresses a closely related question raised in Group 4 below.

2.3 Figure 4: axes and area units

> *Figure 4: How is 10km2 area determined for counts?*
>
> *Figure 4: Given the similar counts/area of the top and bottom panel figures, the figures will be easier to interpret and compare if they used the same axes scales in each panel.*

Author's response: We thank the reviewer for raising both points. Regarding the 10 km² unit: we acknowledge that the label 'fires per 10 km²' in the original submission was incorrect. The active fire counts in Figure 4 are the original raw monthly values from MODIS AF detections per country. As shown below, we have corrected the figure and will revise the caption to accurately reflect the fire seasonality.



2.4 Figure 5: time series overlays

> *Figure 5: It will be helpful to see an overlay of BA on the time series for these regions, and whether the high frequencies correlate with higher BA.*
>
> *Figure 5: Similar to Fig 5 comment, it will be helpful to see an overlay of AF on the time series for these regions, and whether the high BA correlates with higher AF.*

Author's response: This is a useful suggestion that will directly strengthen the presentation of the transboundary fire patterns. We will add another axis of BA to the time-series subplots— BA overlaid on the AF trend subplots (Figure 5, EHA results) and AF overlaid on the BA trend subplots (Figure 6). We hope this can make it easier for readers to assess the correspondence between the two products within each sub-area.

2.5 Labelling and table clarifications

> *Line 375: Perhaps 'southern Turkey' could be changed to south-western Turkey (area 2) to contrast with the southern Turkey (area 1).*
>
> *Table 2: How is 10km2 area determined for counts?*
>
> *Table 3: How do pixels relate to the grid cells?*
>
> *Table 3: Can the table values be further described? Does a value of 2 mean - 2 pixels (?) burned over the entire time period in the entire country for that land cover type?*

Author's response: We thank the reviewer for these detailed observations. We address each point in turn. We will change 'southern Turkey' to 'south-western Turkey' when referring to Area 2 at Line 375 to distinguish it clearly from Area 1.

For table 2, the initial idea was to calculate the active fire density using $10km^2$ cell as it is the grid cell size we used in the entire study including hot spot analysis, trend analysis and correlation. We will consider changing this information to the actual active fire count statistics to accurately reflect the fire activities.

For Table 3, the intention of this table is to show the fire intensity of different land cover classes per country between 2001 and 2022 using BA data. We will add a caption note clarifying that the values represent the range of BA pixel counts (at 500 m resolution) that burned within each land cover class in each country across the full 2001–2022 study period. Therefore, a value of '0–29' means that the cell with the highest fire recurrence in that land cover class and country has BA recorded on 29 separate occasions over 22 years.

Group 3 — Data documentation and description

3.1 MODIS citations and spatial/temporal resolution

> *Line 159: Please add citation for MODIS. Applies to multiple mentions of MODIS products in the manuscript.*
>
> *Line 159: Please include text that Table 1 includes spatial resolution of the products so readers can refer to it.*
>
> *Line 159: Can the authors include temporal resolution of the MODIS products, either in Table 1 or in the main text?*
>
> ***Original manuscript text (Line 159)**: To improve the robustness of fire detection, we combine two MODIS fire products: MCD64A1 for burned area (BA) mapping and MCD14ML for active fire (AF) detections.*
>
> *Line 214: Please include resolution of the product.*

> ***Original manuscript text (Line 214)**: We used the MODIS LC product (MCD12Q1.061), a global product that spans the period from 2001 to the present day, to ensure temporal consistency with the fire dataset.*
>
> *Table 1: Please expand on 'input variable' in the caption for the table.*

Author's response: We thank the reviewer for pointing out these omissions, which we will address throughout the manuscript. We will add the standard MODIS product citations (Giglio et al., 2009 for MCD64A1; Giglio et al., 2018 for MCD14ML) at their first mention and wherever the products are named thereafter. We will add a sentence at Line 159 directing readers to Table 1 for spatial resolutions. We will expand Table 1 to include a temporal resolution column (daily for AF; monthly for BA and EVI/LAI; annual for LC; static for topography and 2020 for population — updated to annual in the revision). The Table 1 caption will be expanded to read: 'Table 1: Characteristics of input datasets used in this study, including data type, variables, time period, original spatial resolution, temporal resolution, and data source.'

For line 214, we will also add citation, spatial and temporal resolution in the text.

3.2 GEE, FIRMS and data filtering

> *Line 169: The relevance of GEE and FIRMS in obtaining data is unclear. Are they the repositories that maintain the products?*
>
> *Line 171: The data selection criteria could be further expanded. Adding more information about the products would help understand the quality of data and which attributes are available for filtering.*
>
> ***Original manuscript text (Line 169-171)**: The MCD64A1 dataset is generated using a hybrid algorithm that combines a burn-sensitive vegetation index, derived from MODIS surface reflectance, with MODIS AF detections (Giglio et al., 2009). On the other hand, MODIS AF data are based on thermal anomalies, providing near-real time fire point data that can capture fire occurrences more rapidly. We used Google Earth Engine (GEE) (Gorelick et al., 2017) and the Fire Information for Resource Management System (FIRMS) to obtain BA and AF data, respectively. We filtered BA data for high-confidence burn dates and AF data with confidence levels exceeding 80 per cent, excluding volcanoes, static sources and offshore detections.*

Author's response: We appreciate the clarification requests on the data description. We will revise Line 169 to clarify the role of each platform: Google Earth Engine (GEE) is a cloud-based geospatial processing platform through which we accessed and processed the MODIS MCD64A1 burned area product using the GEE data catalogue; the Fire Information for Resource Management System (FIRMS) is NASA's active fire data distribution system, from which we downloaded the MCD14ML active fire point data. We will also expand the data filtering description to specify the exact attribute fields used: for BA, we retained pixels with high-confidence burn dates (quality flag ≥ 3); for AF, we retained detections with confidence ≥ 80% and excluded entries flagged as volcanoes, static thermal sources or offshore detections. These filtering steps are important for understanding data quality in a region with known detection challenges.

3.3 SPEI notation and the nine variables

> *Line 183: Please describe the SPEI-X notation.*
>
> *Line 183: Please explain 'nine'. I am guessing this is based on some sliding time window over a year and a definitive explanation will be helpful for readers.*
>
> ***Original manuscript text (Line 169-171)**: Therefore, nine SPEI variables were calculated: SPEI-3 for wet seasons (October to April) and dry seasons (May to September) (minimum, mean, median and maximum values for each).*

Author's response: We thank the reviewer for highlighting this. We will add a sentence defining the SPEI-X notation: the number following SPEI indicates the accumulation period in months over which the standardised precipitation-evapotranspiration deficit is calculated. SPEI-3, for example, reflects water balance conditions over a three-month window, while SPEI-12 reflects conditions over the preceding twelve months. The nine variables are derived as follows: for SPEI-3, we computed four summary statistics (minimum, mean, median, and maximum) separately for the wet season (October–April) and the dry season (May–September), yielding eight variables; the ninth is the annual SPEI-12 value, which captures long-term water balance and is used to test the lagged climate–fire relationship. We will add this explanation explicitly to Section 2.2.2 to make the description clearer.

3.4 Vegetation index: NDVI to EVI

> *Line 189: Please expand NDVI, including its brief description, spatial and temporal resolution, and a description of processing the data.*
>
> ***Original manuscript text (Line 189-191)**: Annual vegetation productivity was assessed using NDVI from combined MODIS Terra (MOD13A1) and Aqua (MYD13A1) products, calculated as annual sums to represent fuel accumulation potential (Abel et al., 2020) and its influence on AF and BA and spread through fuel accumulation.*

Author's response: We thank the reviewer for the suggestions. As noted in our response to Reviewer 1 (Comment 5), we will investigate replacing annual NDVI sums with the Enhanced Vegetation Index (EVI) and Leaf Area Index (LAI), which will be more appropriate for this region due to its reduced sensitivity to atmospheric aerosols including dust, and it might improve performance in dryland and agricultural landscapes. In the revision, the Methods section will include a full description of the chosen vegetation indices, data processing and citations.

3.5 Population data: single year to annual

> *Line 208: I expect variability in population density of a dynamic region like the Middle East over the 20-year period of this study. Can the authors provide further justification of their choice to use the population density from a single more recent year, and its influence on their results?*
>
> *Line 209: Please expand on the definition of constrained vs unconstrained products.*
>
> ***Original manuscript text (Line 208-209)**: While population count is dynamic between 2001 and 2022, the 2020 constrained dataset was selected as a stable proxy for the regional settlement distribution and wildland-urban interface. We prioritise the high spatial resolution of the 2020 constrained model over the temporal variability of the unconstrained annual products, as the former better provides a broad picture of human–fire interactions.*

Author's response: We fully agree with this concern. As described in our response to Reviewer 1 (Comment 2), we will replace the static 2020 WorldPop snapshot with the annual WorldPop unconstrained population density grids for 2001–2020 https://hub.worldpop.org/geodata/listing?id=76), enabling its temporal alignment with the fire and biophysical datasets. Due to the data temporal coverage limitation, we plan to use 2020 population density data for 2021 and 2022 in our study. Using an annual dataset can help us better capture the relationship between fire and populations. In addition, we will add description on explaining the unconstrained method in this paragraph.

Group 4 — Spatial analysis setup

4.1 Section 2.3.1: data cleanup and normalisation

> *Section 2.3.1: The description is unclear about the data cleanup processes undertaken here. Could the authors clarify further, and if possible, with an example schematic? For example, why would only the specified classes reflect spatial misalignments, what is the effect of area differences, what are comparable fractions?*

> ***Original manuscript text (section 2.3.1)**: Using MODIS AF, BA and LC data, our aim is to examine annual trends in AF and BA across the different LC types and affected regions between 2001 and 2022. During this process, we merged water bodies, urban and built-up areas and permanent snow and ice into a single class labelled 'Other' as they constitute only a minor portion of areas with AF/BA. These classes may also reflect spatial misalignments between datasets, classification errors in the MODIS LC product or false-positive detections (commission errors) in the AF/BA products (such as sun glinting on water surfaces). To mitigate the effect of area differences across regions, we also normalised AF and BA values by the area of each region to obtain comparable fractions. By integrating LC with AF and BA data, we generated normalised AF/BA time-series visualisations, fire frequency and land-cover statistics and fire seasonality analyses.*

Author's response: We thank the reviewer for identifying this lack of clarity. We will substantially revise Section 2.3.1 to clarify this process. The classes merged into 'Other' (water bodies, urban/built-up, permanent snow and ice) were excluded for two reasons: first, they account for a small percentage of total AF and BA (AF: 0% from water bodies and permanent snow and ice, and 0.38% from urban/built-up; BA: 0.06% from water bodies and permanent snow and ice, and 0.69% from urban/built-up). Second, AF and BA detections in these classes most likely reflect sensor artefacts, such as sun-glint on water surfaces producing false positive thermal anomalies or edge effects at urban-vegetation boundaries, rather than vegetation fire activity.

The area normalisation is performed by dividing the annual AF counts or BA (km²) for each country by the country's total land area, creating a comparable fraction (fire counts or burned area per km² of country area) that enables direct comparison between countries of very different sizes, such as Iran (1,677,311 km²) and Lebanon (10,136 km²). We will add an illustrative example to the text and consider a simple schematic in Supplementary Material.

4.2 Fishnet grid: size, extent and starting coordinates

> *Line 234: Does the grid size reflect the horizontal and vertical axes, or the diagonal?*
>
> *Line 235: Was a single non-overlapping grid created over the entire study region, or was it created separately for each country? In case of the former, was there a starting x,y coordinate of the grid? Was the grid created based on geodesic distance starting at some x, y?*
>
> ***Original manuscript text (Line 234-235)**: To examine the spatial clustering of fire occurrences, we assessed whether fire counts in spatial units were independent of neighbouring units using three types of spatial autocorrelation analysis applied to active fire points in the Middle East over the study period (Anselin, 1996). The spatial resolution for the fishnet grid was carefully selected after testing multiple options (5 km, 10 km and 20 km) (Text S1 and Figure S1.1, S1.2, S1.3).*

Author's response: We thank the reviewer for these methodological questions. The 10 km grid size refers to the horizontal and vertical dimensions of each square cell (i.e. each cell measures 10 km × 10 km), not the diagonal. A single, continuous fishnet grid was created over the entire study rather than separate grids for each country. By doing this, we ensure that border-area cells are not split between national grids, which is important for detecting the transboundary fire patterns. The grid was created in a customized projected coordinate system for the region using Albers Equal Area Projection so each grid has the same area. We will add these details to Section 2.3.2.

4.3 Queen contiguity, spatial weights and the Getis-Ord statistic

> *Line 236: Can the authors add a sentence describing queen contiguity, and include a reference?*
>
> ***Original manuscript text (Line 236)**: In addition, queen contiguity is selected for the spatial weight matrix as it includes spatial associations by considering all adjacent cells (including those sharing only a corner) as neighbours without inflating the analysis with correlations from spatially disconnected cells.*

Line 244: Is wi,j parametric or non-parametric depending on the distance between cells i and j? Can the authors include its formulation?

Line 245: What is the value of n for the study region?

***Original manuscript text (Line 244-245)**: The null hypothesis (H_0) states that fire occurrences are randomly distributed across the study area. The calculation is presented in Eq. (1).*

$$I = \frac{n}{S_0} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} z_i z_j}{\sum_{i=1}^{n} i} \qquad (1)$$

Where z_i is the deviation of fire count for grid cell i from the mean fire count across all cells. $w_{i,j}$ is the spatial weight between grid cell i and j. n represents the total number of grid cells and S_0 denotes the sum all spatial weights.

Author's response: We appreciate the reviewer's questions. We will add the following explanation to Section 2.3.2: queen contiguity defines two cells as neighbours if they share any boundary or corner, which is analogous to the queen's movement in chess; each cell therefore has up to eight neighbours (Anselin, 1988). Choosing queen contiguity allows us to consider all potential fire spread directions in our hot spot analysis.

Based on the comment from Review 1 to this point, we will correct it and redo the calculation based on the correct formula shown below:

$$\mathrm{I} = \frac{n}{S_0} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} z_i z_j}{\sum_{i=1}^{n} {z_i}^2} \qquad (1)$$

Where z_i is the deviation of fire count for grid cell i from the mean fire count across all cells. $w_{i,j}$ is the spatial weight between grid cell i and j. n represents the total number of grid cells and S_0 denotes the sum all spatial weights.

The spatial weight wi,j is binary (non-parametric): it equals 1 if cells i and j are queen-contiguous neighbours and 0 otherwise, and is row-standardised so that the weights for each cell sum to 1. This is a standard first-order binary contiguity weight matrix and does not vary continuously with distance. The total number of 10 km grid cells covering the study region is n = 31,602.

4.4 Space-time cube: active data, time component, and temporal weights

Line 252: What is active data? Active fire data

***Original manuscript text (Line 252)**: This method requires creation of a space–time cube, stored as a NetCDF (Network Common Data Form) that organises active data into a three-dimensional grid representing spatial locations across time steps.*

Line 258: Does xj have a time component or is it the total count over the entire time period?

Eq 2: Does the statistic assume weights to be spatial only or is that a choice made by the authors to assume uniform temporal weights?

Eq 2: What is the time component in the equation?

***Original manuscript text (Line 258)**: The Getis-Ord Gi* statistic is applied to detect the locations of clusters, including clusters of high fire counts (hotspots) or low fire counts (cold spots). The Getis-Ord Gi* statistic for each cell i (the count of the active fire points) is given by Eq. (2).*

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\left[\frac{n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2}{n-1}\right]}} \quad (2)$$

> *Here, x_j denotes the fire counts at location j; $w_{i,j}$ is the spatial weight between cell i and cell j (neighbouring cells) based on first-order queen contiguity; X and S denote the global mean and standard deviation of all counts; and n is the total number of cells.*

Author's response: We will revise Line 252 to read 'active fire data' throughout. The abbreviation 'active data' was an inadvertent shortening and we apologise for the confusion.

Regarding xj in Equation 2: within the Emerging Hotspot Analysis framework, the Getis-Ord Gi* statistic is calculated separately for each time step (each calendar year from 2001 to 2022). In each annual calculation, xj is the active fire count for cell j in that specific year, not a total across all years.

The space-time cube therefore produces 22 separate Gi* z-scores per cell, with one value generated for each year. These annual z-scores are subsequently subjected to the Mann-Kendall trend test to detect temporal changes in hotspot intensity using one-year interval. The spatial weights wi,j used in Equation 2 are spatial-only and are based on queen contiguity, as described in the previous point. The reason why we chose to use one-year interval is because it produces results that are visually interpretable by showing active fire spatial-temporal hot spots and transboundary pattern. Temporal intervals are treated as implicitly uniform, as the Mann-Kendall test considers each annual Gi* value as a single time step with equal weight.

4.5 EHA category definitions

> *Line 268: It will be helpful to include a table defining each term in the main manuscript as it is essential for the understanding of the methodology results.*
>
> ***Original manuscript text (Line 268)**: By combining the spatial clustering (Gi*) with the temporal trend (Mann–Kendall test), each 10 km cell is categorised following the ArcGIS EHA typology as new, consecutive, intensifying, persistent, diminishing, sporadic, oscillating or historical hotspots (Table S1).*

Author's response: We appreciate this suggestion and agree that the EHA category definitions should be more accessible to readers. However, given that the full typology table from Supplementary material is substantial in size, we propose a compromise to only add the hot spot categories texts and keep the entire table at the Table S1. This way, we can keep the key information in the main text without interrupting the flow of section 2.3.2.

For example, in line 268, we can change it to '...categorised following the ArcGIS EHA typology (Table S1): intensifying hotspots show a statistically significant increase in clustering intensity over time; persistent hotspots are significant in more than 90% of time steps with no trend; sporadic hotspots are significant in the final time step but has been on-again off-again throughout the study period, with fewer than 90% of time steps being significant.'

Group 5 — Statistical tests: Mann-Kendall and Spearman

5.1 Mann-Kendall test: equations, level and normalisation

> *Line 278: What is zero value redundancy?*
>
> *Line 278: Are the MODIS products temporally consistent across the spatial domain, e.g., the products are available at the same time frequency for the domain so that summing the burned pixels is equivalent?*

Original manuscript text (Line 278)*: Following spatial aggregation, monthly BA layers were further aggregated to annual BA; firstly to reduce 0 value redundancy, and secondly to highlight long-term fire extent rather than short-term variability.*

Line 280: Description of the MK test can be moved to the previous section since it was already introduced there.

Original manuscript text (Line 280)*: We evaluated temporal trends in annual BA time series using the Mann-Kendall (MK) trend test over the 22-year period. The MK test is a non-parametric technique widely used in environmental sciences, as it does not require data to be normally distributed and is resistant to the influence of outliers (Karami & Tavakoli, 2025; Kazemzadeh et al., 2022; Kendall, 1938; Lanzante, 1996).*

Eq 3: Are xi at pixel level or grid level?

Line 289: Eq 3 is a summation with (I believe) max value = n(n-1)/2. Is there a missing normalization to convert S to [-1, +1]?

Line 291: Since only the BA is computed here, why would >0 values indicate more frequent fires?

Line 291: I suggest clarifying that the trend is toward recent years, i.e., 'more frequent or severe fires in recent years'.

Line 293: How does the p-value threshold, mentioned on Line 284, relate with the chosen values of -0.5 and 0.5?

Original manuscript text (Line 285-293)*: In this analysis, we used a p-value threshold of 0.05 to determine the statistical significance of the trends. The Mann–Kendall statistic S is computed as Eq. (3):*

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \tag{3}$$

Where x_j and x_k represent pixel values at years j and k, respectively. The function $sgn(x_j - x_k)$ is defined as Eq. (4):

$$sgn(x_j - x_k) = \begin{cases} 1, (x_j - x_k) > 0 \\ 0, (x_j - x_k) = 0 \\ -1, (x_j - x_k) < 0 \end{cases} \tag{4}$$

This formulation evaluates all possible pairs of observations across the time series (2001–2022), returning +1 when BA increases, −1 when BA decreases and 0 when no change is observed. Kendall's tau ranges from −1 to +1, with positive values indicating increasing BA trends (more frequent or severe fires), negative values indicating decreasing trends, and values closer to either extreme reflecting stronger trends. In this study, Kendall's tau values greater than 0.5 and less than -0.5 are defined as strong increasing or decreasing trends, respectively, while values between -0.5 and 0.5 indicate limited trends. These thresholds serve as the primary criteria for interpreting the trend results.

Author's response: We appreciate the reviewer for pointing out the clarification of the method.

Zero value redundancy (Line 278): Aggregating monthly burned area (BA) layers into annual totals reduces the number of zero-value by shifting the analysis from a monthly to an annual scale. Because the analysis is based on pixel-level calculations in a semi-arid region, monthly BA data contain a high proportion of zero values, as many grid cells burn only occasionally. Annual aggregation reduces this sparsity and ensures that the trend test captures fire-season totals rather than month-to-month variability and noise. At the revision, we will update the population data, which can substantially reduce the zero value from the dataset.

Temporal consistency of MODIS products: Yes, the MODIS MCD64A1 burned area product provides globally consistent monthly composites at 500 m spatial resolution for every month from November 2000 to the present.

MK description placement: We agree and will consolidate the Mann-Kendall description into Section 2.3.2 where the test is first introduced, removing the repeated description from Section 2.3.3.

Equation 3: The Mann-Kendall test in Section 2.3.3 operates at the 10 km pixel level by aggregating MODIS burned area from monthly, 500m resolution to yearly, 10km resolution to capture fire trend in a large region. The values xj and xk in Equation 3 represent the annual BA for years j and k respectively within a single pixel's time series. We will clarify this in the text.

Normalisation of S to Kendall's tau: The reviewer is correct that Mann–Kendall statistic (S) itself is not bounded between −1 and +1. Instead, S ranges from $-\frac{n(n-1)}{2}$ to $\frac{n(n-1)}{2}$ where n is the number of observations, which is 22 (years). S is obtained by summing the outputs of the sign function, which returns +1, 0, or −1 for each pairwise comparison depending on whether the later observation is greater than, equal to, or less than the earlier observation. The normalized coefficient used in our interpretation is Kendall's tau is derived from S using tau = $\frac{S}{\frac{n(n-1)}{2}}$. This normalization makes tau's range becomes $-1 \leq tau \leq 1$. The text currently presents S and tau somewhat interchangeably, which is misleading. We will revise the equations and surrounding text to clearly distinguish S (the raw statistic) from tau (the normalised coefficient used for threshold interpretation), and present the full tau formulation.

Positive tau and fire frequency: We thank the reviewer for raising this valid point. Positive Kendall's tau indicates that BA is trending upward over time — meaning larger annual burned areas in more recent years — which implies an increase in either fire extent or fire frequency, or both. We will revise Line 291 to read 'indicating increasing BA trends (larger or more frequent burned areas in recent years)' to make this interpretation explicit.

p-value threshold versus tau thresholds: These are two independent criteria used for different purposes. The p-value threshold of 0.05 is used to determine whether a trend is statistically significant while the tau threshold of ±0.5 are used for map legend classification, visualizing strong trends from weak ones among cells that are already statistically significant. This classification does not alter the original data or statistical test results but provides a clearer visual interpretation of trend magnitude. We will add a sentence to Section 2.3.3 clarifying this two-step interpretation.

5.2 Spearman correlation: framing, cells vs observations, and variable assignment

> *Line 297: Table 1 does not seem to describe data homogenization. Can the authors please describe this further?*
>
> *Line 298: What is meant by 'non-directional measure of association'?*
>
> ***Original manuscript text (Line 297-298)**: To investigate factors influencing fire occurrence and spread, we conducted correlation analyses between AF, BA and other relevant variables after applying data homogenisation and extracting their values to 10 km grid. (Table 1). A decision was made to use a **non-directional measure** of association to assess relationships between our potential factors and fire activity (BA and AF) due to the high complexity and variability of fire dynamics.*
>
> *Line 303: What is the difference between cells and observations, to help understand their different counts?*
>
> *Line 304: Is there a clean separation of cropland and non-cropland BA? For example, can BA fires expand into non-BA fires?*

> *Line 304: Could the authors add information about how each variable was assigned to a grid cell? For example, it is possible that the same grid cell has multiple land cover classifications since its resolution is 500m. How was that grid cell classified for the analysis, and for cropland?*
>
> ***Original manuscript text (Line 303-304)****: Grids with no BA during the study period were excluded from this study, reducing the dataset from 31,602 to 14,642 cells. After removing rows with missing values, the final dataset contained 63,730 observations. We calculated Spearman's rank correlation between annual BA and the selected variables as this is a non-parametric measure that does not assume a linear relationship between variables. As most fires occur in croplands and are intentionally set by humans, we separated the dataset into two versions; one including cropland BA, and one excluding it. This allows us to isolate and examine the extent to which climatic factors influence non-agricultural fires such as those occurring in forests and natural vegetation.*

Author's response: We thank the reviewer for providing feedback on our methods.

Data homogenisation: Data homogenisation refers to the resampling and reprojection of all input layers to a common 10 km grid in a consistent coordinate reference system, prior to the correlation analysis. This step ensures that all variables are spatially registered and comparable within each grid cell. We will add this explanation to Section 2.3.4.

Non-directional measure of association: This phrase refers to the symmetric feature of Spearman's rank correlation, which determined the monotonic relationship between two variables in either direction. We acknowledge this terminology is unnecessarily technical and will replace it with a clearer phrasing such as 'A decision was made to use a non-parametric measure to assess the strength and direction of the relationship between our potential factors and fire activity (BA and AF) due to the high complexity and variability of fire dynamics.'

Cells versus observations: 'Cells' refers to the 10 km spatial grid units (n = 31,602 total; 14,642 with at least one BA detection). 'Observations' refers to the cell-year combinations used in the correlation analysis after removing missing values at the dataset due : for each of the 14,642 spatially active cells, we use all 22 annual values (2001–2022) in the correlation, resulting in 14,642 × 22 ≈ 322,124 potential observations, reduced to 63,730 after removing cell-years with missing covariate values due to grid cells on the border and NA values at current population density data. We will clarify this distinction explicitly in Section 2.3.4. This part will also be modified based on our response to Reviewer 1 using FDR correction, and dataset update to optimize each step and results.

Land cover assignment per grid cell: As the original land cover data is at 500m resolution, each 10km grid cell contains up to 400 land cover pixels of potentially different classes. When building the dataset, we select 'mode' as a method to decide which land cover class to represent, meaning it chose the land cover class with the most pixels as the representative land cover class for the grid cell. This modal assignment means that a cell with, say, 210 cropland pixels and 190 grassland pixels would be classified as cropland. This inevitably introduces some misclassification at land cover boundaries, which we will acknowledge explicitly as a limitation. BA values themselves are not split by land cover within a cell — the full BA of the cell is assigned to the dominant class. For the analysis including all land cover types (Table 4), BA is assigned to the modal LC class of the cell.

Fire spread across land cover boundaries: A fire that ignites in cropland and spreads into adjacent forest or grassland will be detected as BA in the cells it burns through, which will be classified according to their dominant land cover. There is no 'clean' boundary between cropland and non-cropland BA at the fire event level. This is an important limitation and we will note it in the discussion.

Group 6 — Results clarity and quantification

6.1 Gaza, land cover diversity and fire frequency quantification

> *Line 312: Is the limited detection in Gaza because of the country's size combined with the grid layout?*
>
> ***Original manuscript text (Line 312)****: Active fire (AF) and burned area (BA) and activity varied substantially across the eight study regions. While no BA was detected in Gaza due to coarse resolution of the BA product, one AF has been captured (Table 2, Figure 2, Table S2 and Figure S2).*
>
> *Line 326: Can the authors please elaborate on how the conclusion about more diverse land cover types is drawn from Figures 2 and 3? The land cover distribution looks similar for AF and BA, especially in the countries with majority of the fires.*
>
> ***Original manuscript text (Line 326)****: Furthermore, we identify differences between the two fire products; AF captures a more diverse range of land cover types and is able to detect smaller or fragmented fires that are missed by BA.*
>
> *Line 336: Can the authors quantify highest recurrence, e.g., '(20 pixels)'?*
>
> ***Original manuscript text (Line 336)****: Fire frequency – the number of times each pixel burned during the study period – reveals repeated burn patterns across LC types and regions (Table 3).*

Author's response: For Gaza: the absence of BA detection is primarily due to the coarse resolution of MODIS active fire data and small land area (365 km²). However, the MODIS Active fire data detected one fire occurrence, operating through sub-pixel thermal sensitivity and is therefore able to capture fire occurrences that are below the BA detection threshold.

For the AF versus BA land cover diversity claim (Line 326): we will revise the text to be clearer. The argument is that AF detects fire events across a wider range of land cover types than BA. For example, BA data in Lebanon and Israel show fire occurrences primarily in croplands, grasslands, and a small proportion of savannas. In contrast, AF data also detect fire events in shrublands and barren areas, indicating a broader coverage of land cover types.

Regarding table 3, we thank the reviewer for this suggestion. To clarify what Table 3 represents: the range values show how many times individual 500 m pixels burned within a given land cover class and country over the full 2001–2022 study period. For example, the range 0–29 for Turkey's croplands means that the most recurrently burned pixel burned on 29 separate occasions. This reflects the variation in local fire intensity across the country-land cover combination. We would note that spatial recurrence and temporal trends at the regional scale are more directly addressed through our hotspot analysis (Section 3.4) and Mann-Kendall trend analysis (Section 3.5), which identify where fire activity is persistently clustering and whether it is intensifying or diminishing over time.

6.2 Moran's I, EHA classification and Spearman results

> *Line 356: Can the authors quantify significant p-value?*
>
> ***Original manuscript text (Line 356)****: The Global Moran's I analysis yielded a significant p-value and a positive z-score, allowing us to reject the null hypothesis and confirming that fire occurrences are significantly clustered across the study area.*
>
> *Line 358: How is the classification done based on the EHA results?*
>
> ***Original manuscript text (Line 358)****: Building on this, the EHA results reveal diverse AF hotspot patterns that can be classified into intensifying, persistent, sporadic and emerging spatio-temporal categories.*
>
> *Line 385: Suggest adding rho at the beginning of the paragraph to clarify that it refers to the correlation, e.g., Spearman rank correlation, rho, …*

> *Line 385: From Table 4, it appears that significance is determined by p-value. Suggest clarifying this in the text. Is the p-value also calculated as part of the Spearman rank correlation?*
>
> ***Original manuscript text (Line 385)**: The correlations between annual BA and explanatory variables are generally weak (rho < |0.2|) but highly significant, suggesting that fire activity is not governed by any one variable.*
>
> *Line 393: Are the correlations computed between spei_wet of the previous year to the BA the following year? Otherwise, the following statement cannot be established.*
>
> ***Original manuscript text (Line 393)**: Regarding climate, BA shows a significant positive correlation with SPEI during the wet season (such as mean, median and max. SPEI) and the twelve-month SPEI. These positive correlations suggest a moisture-driven fuel accumulation phenomenon, whereby wetter winters promote the growth of fine fuels that later facilitate the spread of fire during the dry season.*
>
> *Line 398: The table footnote is in line with the text. Suggest moving it to the table caption for clarity.*

Author's response: We thank the reviewer for these questions and suggestions.

For Moran's I cluster analysis result (Line 356), we will report the Moran's I p-value explicitly at Line 356 (p < 0.0001, two-tailed, Moran's I index = 0.207307). For the EHA classification (Line 358): each 10 km cell receives a category based on the combination of its Gi* z-score sequence and its Mann-Kendall trend result. For example, a 'persistent hotspot' is a cell that has been a statistically significant hot spot for 90 percent of the time-step intervals with no discernible trend in the intensity of clustering over time. The definition of each class is attached in Supplementary materials.

At Line 385, we will introduce the notation: 'The Spearman rank correlation coefficient (ρ, also referred to as rho)…' to make the symbol explicit from the outset. As responded to Reviewer 1, we will also apply FDR correction for the correlation results.

For the SPEI-3 wet season variable, we extracted monthly SPEI-3 values from October of year t−1 through April of year t, then summarises these as mean, median, minimum and maximum across the seven months. Since each monthly SPEI-3 file already reflects a three-month accumulation window ending at that month, the wet season variable collectively captures moisture conditions from approximately August of year t−1 through April of year t. For example: for wet season in a target year (e.g. 2005):

Previous year 2004:

- SPEI03_2004_10 → covers August – October 2004
- SPEI03_2004_11 → covers September – November 2004
- SPEI03_2004_12 → covers October – December 2004

Cross-year between 2004 and 2005:

- SPEI03_2005_01 → covers November 2004 – January 2005
- SPEI03_2005_02 → covers December 2004 – February 2005

Targeted year 2005:

- SPEI03_2005_03 → covers January – March 2005
- SPEI03_2005_04 → covers February – April 2005

For SPEI-12, we extract the SPEI-12 for December of year t−1, which accumulates the full water balance from January to December of year t−1, and correlate it against the annual BA of year t. This constitutes a cross-year lag and supports the fuel accumulation hypothesis described at Line 393.

We will revise the manuscript to describe these two mechanisms separately and more precisely: the SPEI-3 wet season relationship reflects within-year antecedent moisture promoting fuel growth ahead of the fire season, while the SPEI-12 relationship reflects a cross-year lagged effect whereby the previous year's overall water balance influences the following year's fire risk through fuel accumulation.

Regarding table 4 (Line 398), we will move the Table 4 footnote into the table caption as suggested, improving clarity meeting the standard journal format.

Group 7 — Discussion framing and Results–Discussion linkage

7.1 Arc pattern, supplementary figures and Results–Discussion linkage

> *Line 430: The arc shaped fire pattern has not been highlighted in previous manuscript sections but listed here as an observation.*
>
> ***Original manuscript text (Line 430)**: Our findings yield four insights. First, we identify an arc-shaped transboundary fire pattern which extends across the Mediterranean towards the semi-arid steppe climate zone, along the borders of Turkey, Syria, Iraq and Iran, highlighting the importance of transboundary fire management.*
>
> *Section 3.4: Would it be possible to associate the significant peaks in Fig 5 with associated major fire events? This would bolster the authors' findings, help the readers understand the underlying reasons for the peaks, and provide assurance that these are not data anomalies. After reading the Discussion section, I realized that this analysis was performed there. It would be helpful for future readers if the manuscript was reorganized to include that analysis along with the statistical observations, or at least include a reference to the explanations presented in the Discussion section.*
>
> *Line 444: Since the statement is included as one of the key conclusions in the main manuscript, I would suggest moving this material and any associated text from supplementary to main manuscript. Also applies to Line 507.*
>
> ***Original manuscript text (Line 444)**: Instead, the fire regime in the Mediterranean climate zone exhibits spatial heterogeneity, which suggests that factors such as topography, fuel types and human activities are also critical elements that alter the fire regime. Even within two climate regions, spatial heterogeneity marked by variations in elevation, temperature, precipitation and land cover (see Figure S4) creates distinct fire behaviour.*
>
> ***Original manuscript text (Line 507)**: In addition, the most significant trends form a prominent arc-shaped pattern tracing the borders of Turkey, Syria, Iraq and Iran; this pattern is also evident in the fire frequency map shown in Figure S4.*

Author's response: We thank the reviewer for these valuable inputs on the results and discussion. In this revision, we will add a brief summary sentence at the end of Section 3.5 (BA trend analysis) describing our finding on the arc-shaped fire pattern.

Regarding mentioning the drivers of fire at Section 3.4 (AF spatial-temporal hotspots), we agree that readers would benefit from clearer signposting between the statistical results and the event-level interpretations in the Discussion. However, we consider it methodologically appropriate to keep the identification of specific fire events and their drivers in the Discussion rather than the Results, since attributing peaks to particular causes (e.g. the 2021 Turkey megafire, the 2019 Syria–Iraq fire anomaly) constitutes interpretation rather than statistical reporting. Moving this material into the Results would conflate observation with explanation. We understand the concern from the reviewer when it becomes difficult for readers to understand the contexts or drivers of the fire events, therefore, we will add a brief reference sentence at the end of Section 3.4, directing readers to the relevant Discussion subsection.

We thank the reviewer for the suggestion on moving Figure S4 to the Discussion section to support our argument at Line 444 and Line 507. Rather than moving the entire six-panel figure into the main manuscript, we would like to show only the top panel of Figure S4 into the main text, which are the fire frequency panel and climate region boundaries. This figure supports our statements by showing the arc-shaped fire frequency pattern, and provides the spatial heterogeneity context referenced at Line 444. We will extract this panel and add it as a numbered figure in the main manuscript, positioned in Section 4.1. The remaining panels showing elevation, land cover, temperature and precipitation will remain in the Supplementary Material as background context, with a clear reference in the caption directing readers to the full figure.

7.2 Spatial heterogeneity, physical evidence and terminology

> *Line 401: Does spatial heterogeneity refer to no consistent correlation across areas with explanatory variables? The term can be further clarified.*
>
> ***Original manuscript text (Line 401)**: The correlation analysis of the eight sub-areas (Areas A, B, C, D from the AF EHA and Areas 1, 2, 3, 4 from the BA trend analysis) reveals spatial heterogeneity (Figure 7). Their pattern can be classified into three fire regime types: Sect.3.6.1 Agricultural and flatland, Sect.3.6.2 Mountainous and transboundary, and Sect.3.6.3 Emergent forest.*
>
> *Line 443: Similar to a previous comment, the term 'spatial heterogeneity' is not sufficiently defined.*
>
> ***Original manuscript text (Line 443)**: However, our findings indicate that a Mediterranean climate alone is not a reliable predictor of fire activity. Instead, the fire regime in the Mediterranean climate zone exhibits spatial heterogeneity, which suggests that factors such as topography, fuel types and human activities are also critical elements that alter the fire regime.*
>
> *Section 3.6.1: Along with the statistical observations, are the authors able to comment on the reasons behind the observations? Without them, it is not possible to ascertain whether the observations are supported by physical evidence. Also applies to section 3.6.2-3.*
>
> ***Original manuscript text (section 3.6.1 Agricultural and flatland fire regime)**: This is located in southern Turkey (Areas 1 and B) and the Turkey–Syria border region (Areas 2 and C), where fire activity is concentrated in low-elevation croplands and shrublands. Despite their geographic proximity, these areas exhibit different responses to moisture. In southern Turkey, Area 1 (BA) exhibits a significant positive correlation with wet-season SPEI, while the overlapping Area B (AF) exhibits a negative relationship. Similarly, along the Turkey–Syria border, Area 2 (BA) displays a negative correlation with wet-season SPEI, in contrast to the positive correlation observed in the corresponding Area C (AF). This indicates that within the same localised region, BA and AF datasets respond differently to wet-season moisture variables.*

Author's response: We will define 'spatial heterogeneity' explicitly at its first use and use consistent language throughout. In this context, spatial heterogeneity in fire-climate relationships means that the direction, strength and significance of correlations between fire activity and explanatory variables differ substantially across sub-regions. This is a substantively important finding because it implies that no single climate or topographic variable governs fire across the whole region.

We agree that Sections 3.6.1–3.6.3 are currently largely statistical, and that contextualising the correlations with physical and ecological reasoning would substantially strengthen them. However, we consider detailed causal explanations, such as why the Zagros Mountains show positive wet-season SPEI correlations or why BA and AF respond differently to moisture in the same area. We think it is more appropriate to place the interpretation in the Discussion, where these issues are addressed in Section 4.6.

To provide physical contexts to reader at the Results section, we will add one brief contextualising sentence per sub-area at the start of each Section 3.6 subsection, describing the dominant ecosystem and land use type of the area. For example, Section 3.6.1 covers intensively cultivated lowland agricultural plains, whereas Section 3.6.2 covers mountainous landscape with oak woodlands. We will also add forward-reference sentences at the end of each subsection directing readers to the relevant part of Section 4.6 for more detailed interpretations. This follows the same approach adopted for Section 3.4.

7.3 Cropland analysis, lagged effects and attribution framing

> *Line 433: The cropland and non-cropland analysis is shown for Spearman correlation but other distributions are not included in the main manuscript. Since 74% contribution is highlighted as an observation throughout the manuscript, I suggest including further analysis of cropland vs non cropland distribution of fires within the main manuscript.*
>
> *Line 433: The lagged event is not sufficiently demonstrated as it is unclear from the analysis whether the correlations were developed with lagged parameters.*
>
> ***Original manuscript text (Line 443)**: Second, we show that fire activities occur mostly in human-dominated landscapes, with croplands accounting for 74 per cent of the BA. Third, we found evidence for a 'lagged climate effect', whereby antecedent wet-season moisture assists fuel accumulation and promotes subsequent fire activity in several sub-areas.*
>
> *Line 435: Since the correlation is developed between the dependent variable with a single explanatory variable, wouldn't this constitute univariate attribution?*
>
> ***Original manuscript text (Line 435)**: Fourth, our analysis shows the limitations of bivariate attribution in this region. The weak correlations between fire and single variables underscore the complexity of multi-causal fire regimes in which agricultural practices, land management and policy factors interact with biophysical conditions to shape fire activity.*
>
> *Line 442: The authors have performed correlation analysis, but not demonstrated predictive capability of different variables (which would require time lagged modeling), to support this statement.*
>
> ***Original manuscript text (Line 442)**: Instead, the fire regime in the Mediterranean climate zone exhibits spatial heterogeneity, which suggests that factors such as topography, fuel types and human activities are also critical elements that alter the fire regime.*

Author's response: We thank the reviewer for pointing out the lack of explanation of results and language issues.

Cropland/non-cropland burned area (Line 433): We agree that the 74% burned area are shown on croplands is one of our central findings and should be elaborated more. In addition to the correlation comparison table between cropland and non-cropland fire (Table 4), we will add a brief supplementary figure or table showing the proportional distribution of total BA across land cover types per country, and reference it in the main text.

Lagged correlations (Line 433): As addressed in response section 6.2 (comment on Line 393), the SPEI-3 wet season variable captures antecedent cross-year moisture (October in year *t−1* through April in year *t* preceding the June–August fire season), and SPEI-12 constitutes a cross-year lagged variable, which includes the full previous calendar year water balance. Together these provide a basis for the moisture lagged effect narrative. In the revision, as mentioned at the response to Line 393, we will rewrite the relevant Methods paragraph to describe these temporal structures explicitly.

Univariate versus bivariate attribution (Line 435): We thank the reviewer for raising this concern. The method we are using, Spearman correlation analysis between two variables — one dependent (BA) and one independent (e.g. SPEI), is a bivariate analysis, since it examines the relationship between two variables simultaneously. Univariate analysis would describe a single variable in isolation, such as its distribution or summary statistics. However, we understand the reviewer's concern: computing a series of bivariate correlations does not mean causal modelling or regression, and the term 'attribution' that we used, implies a stronger claim than correlation can support. We will revise the Discussion language accordingly, replacing 'bivariate attribution' with 'bivariate correlation' and clearly stating that the results should not be interpreted as variable-specific attribution of fire activity.

Predictive capability (Line 442): We agree entirely and this is consistent with the language revision. We will revise language in Section 4.1 or elsewhere that implies the correlation analysis demonstrates predictive capability, and replace it with language that accurately reflects what Spearman's correlation can establish: the existence and direction of statistical associations, not the ability to forecast fire activity.

7.4 Fire seasonality contradiction

> *Line 487: This observation has not been highlighted in previous sections and to some extent, contradict the statement on line 349: 'Most regions exhibit bimodal fire seasonality'.*
>
> ***Original manuscript text (Line 349)**: Both datasets reveal a consistent summer fire season across the study area, with peak activity concentrated between June and August. Most regions exhibit bimodal fire seasonality, with a primary summer peak and a secondary peak typically occurring in spring or autumn.*
>
> ***Original manuscript text (Line 487)**: Although dual peaks appear in a number of areas, only Israel and Lebanon show distinct fire peaks in both the dry and wet seasons. In these areas, the fire regime is dominated less by agricultural cycles and more by transitional synoptic systems and seasonal climate variability, leading to bimodal fire seasonality.*

Author's response:

We thank the reviewer for highlighting these contradictory formulations. The contradiction arises from how the term 'bimodal' is used at Lines 349 and 487. In the revision, we will classify the fire seasonality based on the result from the updated fire seasonality figure as shown in comment 2.3. Turkey and Syria show bimodality with peaks in June–July and September within dry season; Iran shows an asymmetric bimodal pattern with a dominant May–June peak and smaller peaks in February and November. Iraq shows unimodal with a single June–July summer peak; Israel and Lebanon show a bimodal pattern spanning the dry season (May–July) and the dry-to-wet season transition (October–November); and the West Bank shows a secondary AF peak in November without a corresponding BA result, suggesting small-scale fires that do not spread extensively. We will revise Line 349 and Section 4.4 accordingly to ensure the terminology is precise and consistent throughout.

We are grateful for the reviewer's constructive feedback and believe that the revisions will substantially enhance the manuscript. We welcome the opportunity to revise and resubmit the paper for further consideration.

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