egusphere-2025-4859 – Author's response to Anonymous Referee 2

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Referee comments are written in blue italics; author's responses are written in normal font; and proposed changes are highlighted in green font.

The manuscript entitled "Exposure of Settlements to Wildfires in a Transboundary Wildland-Urban-Interface Region in Central Europe" presents the application of wildfire spread modeling approaches (based on FlamMap) in a study area of Central Europe to analyze exposure to settlements to wildfires. The work also describes an interactive web-based map that was developed to inform local stakeholders about potential fire behavior and exposure in the study area.

The manuscript is overall interesting, particularly because it covers an area characterized by limited wildfire activity and low danger conditions if compared to other Southern European areas. In this sense, the manuscript informs local stakeholders about wildfire issues in a region that can be affected by more wildfires in future years due to climate and land use changes.

We thank the reviewer for the detailed review and helpful suggestions. We have revised the manuscript accordingly and provide point-by-point responses below.

Nevertheless, some sections of the study need to be improved, and some methods and results should be better explained or improved, as described more specifically in later lines. Some parts of the manuscript should be carefully re-organized, as for instance some sentences/sections of the Results should be moved to Discussions or Methods. Moreover, there is a need to reinforce the Introduction section and the state of the art, considering that the modelling approach proposed is quite common, and the results obtained are similar to a number of similar studies carried out in the US or in Southern Europe. The Discussion should also be improved.

In the following lines, the specific comments about the manuscript:

L25-80: In the Introduction section, the state of the art (particularly for the "wildfire exposure" and the "wildfire modeling" parts, which represent the key of this manuscript) is quite limited, and the review of relevant literature is not exhaustive. For instance, the model adopted for the modeling exercise (FlamMap) is not mentioned.

We thank the reviewer for this suggestion. We have expanded the Introduction to better reflect the state of the art on wildfire exposure assessment and fire modelling by adding relevant references after L66:

"Such spatially explicit approaches have been increasingly applied in wildfire exposure assessments, particularly in wildland–urban interface contexts, where the combination of fire likelihood, potential fire behaviour, and the location of assets is used to identify areas of elevated exposure (Argañaraz et al., 2017; Haas et al., 2013; Scott et al., 2013)."

We also added some information on FlamMap, to more clearly position it within the existing literature on wildfire hazard and exposure modelling with a focus on Europe. After L70:

"FlamMap is the tool chosen here for wildfire modelling. FlamMap is a fire analysis application developed by the Missoula Fire Sciences Laboratory(FlamMap - Missoula Fire Sciences Laboratory, 2026). FlamMap has the advantage of being able to visualise fire behaviour characteristics directly related to exposure such as flame length and burn probability, in the form of geolocated rasters, which facilitates the derivation of settlements' exposure (Peterson et al., 2007). It is commonly used to analyse fire behaviour in European settings. For example, Salis et al. (2009, 2012) used FlamMap to assess wildfire severity in Italy, Mitsopoulos et al. (2016) used it for a Greek landscape, Sá et al. (2022) used it in Portugal, and Alcasena et al. (2017, 2018) in Spain. For applications in Central Europe, FlamMap has been used only recently (Kudláčková et al., 2024), which is however related to the rather limited wildfire research in that region."

L84-89: The authors report that the study area is 700 km2 in both Germany and the Czech Republic. Please indicate the extent of the German area vs the Czech Republic area.

We will amend this as suggested, and additionally be more specific about the extent of the study area. The new sentence will read as follows:

"The study area extends across a transboundary area of 720 km² on both sides of the River Elbe in Germany (322 km²) and the Czech Republic (398 km²)."

L105-109: A short description of the main topographic characteristics of the study area would be important. In addition, I would recommend adding some more information about the main land uses of the study area (e.g.: percentage of agricultural areas? Urban/anthropic areas? Main forests, apart from Picea abies?)

We agree with the reviewer that more context would benefit the better understanding of the study area. We therefore propose adding the following text after L88:

The area is dominated by forests (69%) and grasslands (17%), with croplands also covering a substantial share (10%) - mainly on the German side of the border (Copernicus Land Monitoring Service, 2025). Built-up areas account for 2% of the study area. These are primarily located in the south (e.g., towns of Děčín, Jílové, and Česká Kamenice) and on the German side along the Elbe River (e.g., towns of Stadt Wehlen, Königstein, and Bad Schandau; Figure 1). The study area is characterized by prominent sandstone formations, rocky outcrops, and steep cliffs. Elevations range from approximately 200 (Elbe river valley) to 723 m (Děčínský Sněžník), and this rugged topography poses substantial challenges for firefighting operations."

For a more accurate description of the local forests, we would replace the sentence on L103 with the following:
"The forested parts of the study area are largely dominated by Norway spruce (Picea abies), although pines (Pinus sp.), larch (Larix sp.), European beech (Fagus sylvatica) and silver birch (Betula pendula) are also present (Beetz et al., 2024)."

A similar consideration is valid for the fire regime (e.g.: fire season months, average area burned, and fire number per year).
We agree that additional context on the local fire regime would improve the manuscript. We therefore recommend adding the following paragraph right before L96:
"Based on the historical ignition datasets described in Sect. 2.3.1, wildfire occurrence in the study area is predominantly human-caused. For the German (Saxon) part, the most frequently reported ignition category is open fires by other persons (41.7%), followed by unknown or unclear causes (26.6% combined), while lightning accounts for 10% of cases. For the Czech part, the dominant ignition categories are setting fires in the countryside/burning grass (44.2%) and smoking (37.4%), whereas lightning represents 3.1% of cases (other natural causes <2%). Based on the available records used in this study, the Czech dataset (2016–2020) includes 163 ignitions (32.6 per year), while the German dataset (2008–2020) includes 60 ignitions (~4.6 per year). Seasonality differs between the two sides of the border: in Saxony, ignitions are strongly concentrated in late spring and summer (April to August: 80% of cases; May to June alone: 50%), whereas in Czech Republic ignitions are more broadly distributed across the year (April to August: 67.5%), with a secondary contribution in October and November (~16.6%). The available records do not include burned-area information; therefore, fire size statistics could not be derived".

L127-133: To produce the flame length outputs, I suppose the authors analyzed the flame length probability (FLP) file based on the MTT simulations, and then derived the conditional flame length. Please clarify.
We thank the reviewer for this important comment. We clarify that the flame length outputs used in this study were not derived from the MTT-based Flame Length Probability (FLP) output and subsequent Conditional Flame Length (CFL) calculation. Instead, we used the Basic Fire Behaviour flame length (FL) output from FlamMap.
This choice was made because our objective was not to describe fire behaviour within the simulated fire perimeters, but to characterise the potential intensity of areas across the entirety of our study area, including locations that did not burn in a given simulation run. MTT-based outputs such as FLP or burn probability are restricted to the area reached by the simulated fire spread (Finney, 2006). As a result, they are well suited to analysing the behaviour of a specific simulated wildfire event, but are less suitable for the construction of a spatially continuous exposure product intended to support comparison across the full study area.

To illustrate this, we added Figures AC2 1, AC2 2 and AC2 3. Figure AC2 1 compares burn probability outputs from one-day and three-day FlamMap simulations under the same southerly wind conditions and shows that the one-day simulation leaves substantial parts of the study area unburned. Similarly, Figure AC2 2 demonstrates the same issue for FLP-derived CFL, which like burn probability (another MTT-derived output) is only produced for areas reached by the simulated fire. In contrast, the Basic Fire Behaviour FL output, shown in Figure AC2 3, provides spatially continuous information on potential fire intensity, leaving areas unburned only where fuels are non-burnable, rather than because a simulated fire did not reach them within the modelled time frame. This distinction is particularly important in our study area because some locations, such as agricultural areas in the west, may exhibit low CFL because they are not consistently reached by simulated fires, while still showing very high potential FL (these are the large purple areas concentrated on the western part of the study area, as shown in Figure AC2 3). These areas may therefore have considerable hazard potential even if they are not frequently burned in the current simulations. This consideration is already reflected in the discussion of future development of a weighted hazard or exposure index (L559–565), where we highlight that areas with high potential flame length but low burn probability require greater attention in the context of a possible future exposure index. Finally, although Basic Fire Behaviour FL remains relatively consistent across scenarios, as also observed in Figure 3 and Figure AC2 3, we consider this limitation acceptable because the alternative, CFL, would restrict the intensity assessment to only those areas reached by the simulated fire.

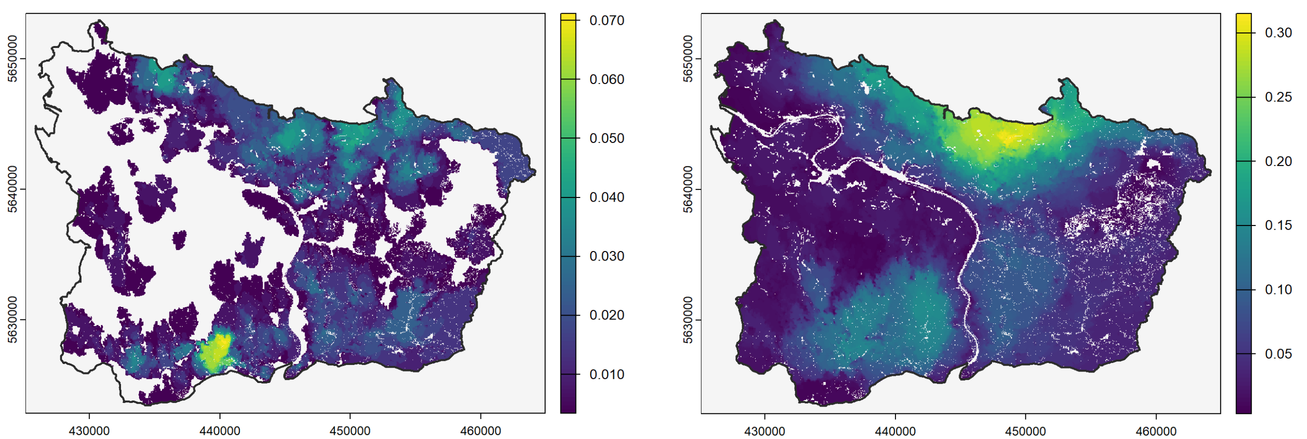

Figure AC2 1: Comparison of MTT-derived burn probability, with zero values masked, from two FlamMap simulations using the same southerly wind conditions derived from WBI = 5. The left panel shows the 1-day simulation, and the right panel the 3-day simulation.

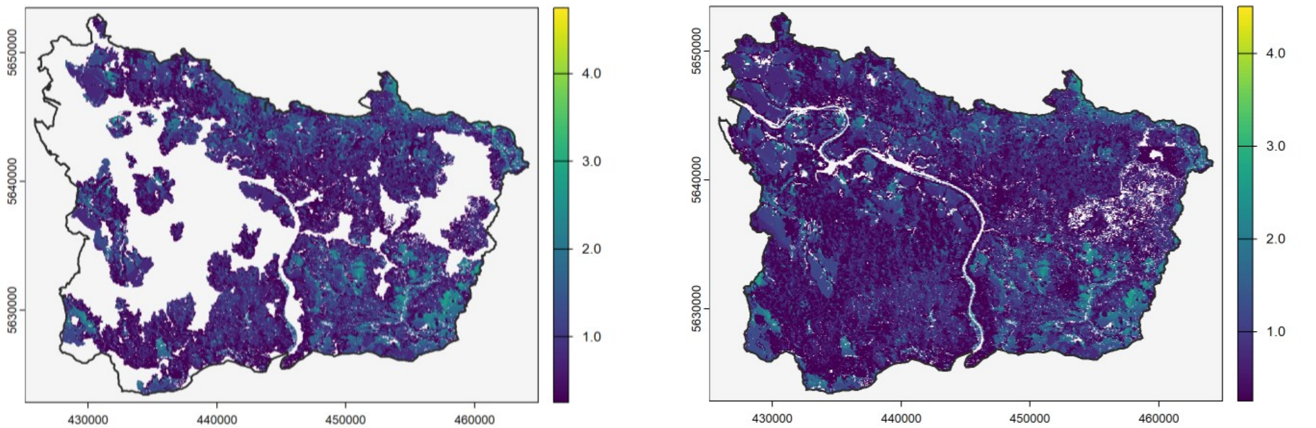

Figure AC2 2: Comparison of MTT-derived Conditional Flame Length, with zero values masked, from two FlamMap simulations using the same southerly wind conditions derived from WBI = 5. The left panel shows the 1-day simulation, and the right panel the 3-day simulation.

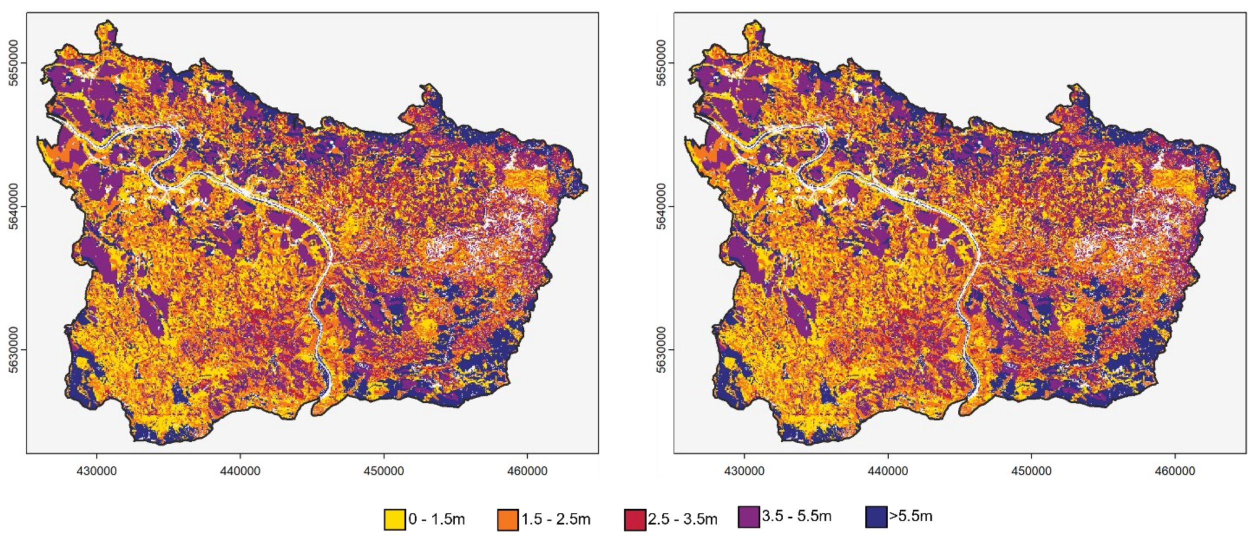

Figure AC2 3: Comparison of Basic Fire Behaviour-derived Flame Length, with zero values masked, from two FlamMap simulations using the same southerly wind conditions derived from WBI = 5. The left panel shows the 1-day simulation, and the right panel the 3-day simulation. The classes used are the same as in the main publication.

In addition, please report in the discussion why other outputs of FlamMap (e.g.: fire size; potential crown fire occurrence) were not used to analyze wildfire hazard or exposure in the study area.

We thank the reviewer for raising this point. Fire size was not included in this study, because although informative, it is not directly suited to the exposure framework adopted here. Our objective was to showcase the juxtaposition of one spatially explicit likelihood metric and one spatially explicit intensity metric with the location of exposed assets. For this purpose, burn probability and flame length were considered the most appropriate FlamMap outputs, as they illustrate these metrics and are both commonly used in wildfire hazard and exposure assessments (e.g., Sá et al., 2022).

Crown fires, as well as spotting, were not modelled because the fire-modelling landscape lacked the required canopy layers (canopy height, canopy base height, and canopy bulk density). We did consider incorporating these layers using the European-wide canopy/fuel dataset produced within the European Commission's FIRE-RES project (Kutchartt et al., 2024; Pirotti et al., 2023), which provides these canopy variables for our study area. However, these canopy data represent conditions around 2020, whereas the study area experienced substantial bark-beetle-related canopy degradation between 2020 and the 2022 wildfire. Without site-specific validation (e.g., field-based verification of canopy structure as in Heisig et al., 2022), using these canopy layers risked introducing uncontrolled bias in crown-fire (and hence spotting) occurrence. Given the scope of the study, we therefore did not include crown-fire/spotting and explicitly acknowledge this as a limitation on L542-543 of the Limitations. For better clarity, we recommend rephrasing this part to:

"As up-to-date data on canopy structure that is representative of bark-beetle-affected conditions were not available, crown fires and thus spotting were not modelled. Consequently, fire spread and intensity may be underestimated under extreme weather, especially where firebrand transport could enable rapid downwind growth or cross-barrier spread.".

L142-155: This part is quite long but needs to be improved. Please indicate the reference study period for the fire ignition data. In addition, the methods used to determine/assign fire ignitions and related probabilities for the simulations are not clear and should be presented with more details.

Thank you for this comment which is in line with Reviewer 1, who also suggested to revise this paragraph. We propose to change the text in reply to both reviewers as:

Historical forest fire ignition data (60 ignitions, spanning 2008-2020) for the German part of the study area were provided by the Saxon State Authority for Forestry (Staatsbetrieb Sachsenforst, 2023). Additionally, we also included known locations in the National Park Saxon Switzerland considered particularly susceptible to future ignitions in the German part of the study area. These comprised parking areas, viewing points, legal fire pits, and legal and illegal rock shelters ("Boofen" in German), totalling 697 sites. At those sites, camp fires are often ignited but did not result in a forest fire so far. Ignition locations from the Czech part (163 ignitions, spanning 2016-2020) were acquired from the Fire Rescue Service of the Czech Republic (Hasičský záchranný sbor České republiky, 2023). Neither dataset is publicly available. The ignition location of the 2022 fire was manually added to the dataset as it had not yet been included in the respective dataset. The joint datasets encompassed the locations of 921 ignition points. To balance ignition density between the German and Czech parts of the study area, we calculated the target number of ignition points for each side—based on the lower Czech density—and randomly subsampled the German ignition locations to match this target. The final number of ignition points was 363. These can be seen in Figure D1.

L163-164: The authors report that "Dead fuel moistures in non-beetle killed areas were set to 3, 4, and 5% for the 1-hr, 10-hr, and 100-hr dead fuels, respectively". Please clarify if these data were only applied to specific forest areas, or to the whole set of fuel models with dead fuels (e.g.: herbaceous fuel models). In my opinion, these values are very low, and might be observed only in days characterized by very extreme conditions, not in days with medium or high WDI values, particularly in Central Europe. As the authors know, considering that the simulations were carried out using fixed fuel moisture, these values are crucial and can heavily affect the simulated spread rate, fire intensity, and fire size of the fire simulations. Please clarify.

We thank the reviewer for this important comment and acknowledge that the previously used dead fuel moisture values of 3, 4, and 5% are very low and may be too extreme to be considered representative across all simulated scenarios, particularly for conditions corresponding to WBI classes 3 and 4. We will therefore revise the fuel moisture parameterisation. For the revised model runs, we will use locally measured fuel moisture information from 10h fuel sticks and destructive samples that we took since 2023 (Kranz et al., 2025). Two of our fuel moisture sites are located within the study area in the Saxon Switzerland National Park, one situated in a bark beetle-disturbed spruce stand, and the other in a non-disturbed beech forest. We also conducted bi-weekly to monthly 1h and 100h dead fuel moisture content from samples of litter and fine woody debris respectively. Kranz et al. (2025) show strong negative correlation between the 10h fuel stick measurements and Fire Weather Index (on which the WBI is based).

Based on this information, we will estimate typical values for 1, 10 and 100h dead fuel moisture values for bark-beetle-affected and non-affected forest stands for the revised paper. These values will be grouped according to the corresponding WBI classes. We will clarify in the revised manuscript which fuel models these values are applied to and update the simulations accordingly.

L170-171: Again, the use of a constant fuel moisture value for live herbaceous vegetation and live woody fuels can be problematic, considering the range medium-high-very high conditions used for the simulations. Please clarify if these values reflect the conditions observed in very high-risk days, or if these are average fuel moisture values when WDI is above 3.

We thank the reviewer for this comment. Similarly to the above reply, we will use the data from destructive LFMC measurements from Kranz et al. (2025) to derive typical LFMC values for the different WBI levels. Kranz et al. (2025) used destructively sampled LFMC for different fuel size classes in the growing season of 2023, and interpolated Sentinel-1 and Sentinel-3 times series to derive daily LFMC values for the study area of this paper.

L203-227: It is not clear why this section is presented in this part, as it is not related to the fire spread modeling part.

We thank the reviewer for this comment. While Section 2.3.3 is not directly related to the fire modelling stage, Section 2.3 was designed as a general "Datasets" section, covering all input data used in the study, including those for hazard modelling as well as exposure assessment and support capability indicators. For this reason, Section 2.3.3 was retained within this section. We nevertheless recommend changing its name to "Ancillary datasets" for clarity.

Moreover, how were the locations of fire stations and the local transportation infrastructure used to characterize wildfire exposure? Or were the locations of fire stations and the local transportation infrastructure only determined for visualization purposes in the web-app? Please clarify

The fire stations and the transportation network were not used as part of our exposure calculation, as was e.g., done in Oliveira et al. (2020), where proximity to fire stations via the paved road network are used to quantify coping capacity. Instead, they were included as contextual support capability layers. In the interactive web map, these layers served two purposes: Firstly, they were used in the user activity of both the usability and usefulness questionnaires, which asked participants to identify a route from a settlement to the nearest fire station under a defined wildfire scenario. Secondly, they informed the stakeholder discussion by being included among the layers evaluated for their usefulness in the stakeholders' work. We have clarified this distinction by altering the first paragraph of Section 2.3.3, to avoid the impression that these layers were used to quantify exposure:

"For the assessment of wildfire exposure, we included local settlements and building infrastructure. In addition, fire stations and the local transportation network were included as contextual support-capability indicators to support user orientation and route planning in the interactive web map and to enable the task-based evaluation described in Sect. 3.5. These were not used as input variables in the exposure calculation."

L228-234: The authors state that "While ignition locations and fuel moisture were held constant based on historical observations (Sect. 2.3.1), different scenarios for fire duration and wind conditions were selected to give realistic outputs in terms of BP and FL. The different factors resulted in nine different wildfire scenarios". So they are considering 9 scenarios. But then, in L271-272, they indicate that "We then run FlamMap with the three most prominent wind directions and associated wind speeds for the three scenarios of fire duration, resulting in twenty-seven model simulations". Here, they report 27 scenarios. In my opinion, it is more correct and clearer to a reader to report, in this part of the manuscript, that the work is based on 27 simulations (3 fire duration x 3 wind speed x 3 wind directions).

We thank the reviewer for this helpful suggestion. We agree that reporting the total number of model runs more explicitly improves clarity. In the manuscript, we distinguish between "scenarios," which refer to the combinations of fire duration and wind conditions, and "simulations," which refer to the individual FlamMap runs based on these combinations. To make this clearer, the sentence in L271–272 has been revised to:

"We then run FlamMap with the three most prominent wind directions and associated wind speeds for the three scenarios of fire duration, resulting in twenty-seven model simulations (3 fire duration × 3 wind speed × 3 wind directions)."

L257-270: If I am right, the weather data and the danger analysis are based on the data coming from the German side, while the Czech Republic zone of the study area is not covered. Are the zones similar in terms of dominant winds, danger levels, etc.? Please provide more information on this point.

We thank the reviewer for this comment, and would like to provide clarifications on this matter. The selection of a German weather station follows from our decision to use the German fire-weather index Waldbrandgefahrenindex (WBI). WBI is an operational index available consistently for German municipalities, whereas an equivalent WBI time series is not available for the Czech part of the study area. We therefore used the municipality of Bad Schandau to derive WBI values, as it lies entirely within the study area and directly borders the Czech part (Figure D1). Hourly wind observations were taken from the nearby Lichtenhain-Mittelndorf station, which is close to Bad Schandau and also located within the study area (Figure 1).
WBI is used here solely to stratify days into fire-weather danger categories (WBI 3-5) in order to derive typical wind-direction frequencies and mean wind speeds under different fire-danger conditions, not to compare national fire-danger systems. Given the close proximity to the border and the contiguous study region with similar heterogeneity in topography, these wind statistics are expected to be representative for the cross-border study area. We amended L557-558 in the Limitations section as:
"We used weather data from a meteorological station in the centre of the study region and assume that this station is representative for the entire area. However, given the complex topography and elevation differences, micro-climatic conditions are quite different in the study region (Wild et al., 2019) which also affects fuel moisture (Kranz et al., 2025). Currently, we cannot account for this microclimatic variability in fire modelling."

L300-308: This part is not related to wildfire exposure, but is related to the web-app. This should be modified or presented in another section.

We suggest moving this part, to the Methodology. Along with the sections from L440-445 and L462-470, they would serve as the new section 2.7 "Interactive web map and questionnaire design".

L361-369: This is not related to results and should be moved to Discussions.

This paragraph will be moved to section 4.2 of the Discussion.

L386: This section could be moved to Methods, or after the wildfire modeling part of the results.

This section will be moved to right after section 3.1 of the Results.

L403: Again, this part is not related to results and should be presented in the methods. In addition, the validation part is quite complicated to understand, and needs to be revised.

We revised the validation section in line with the suggestions of Reviewer 1. Given the emphasis placed by the reviewer on the evaluation of the fire model simulations, we prefer to retain some parts of the validation component in the Results section, but others will now go to the new methodology section 2.7: "Methodology for the evaluation of wildfire modelling".

L439: This section merges information that should be included in the methods, and some parts that could be presented in the results. In general, I would recommend simplifying the presentation of the results obtained with the surveys

We agree that L440-445 and L462-470, which describe the design of the questionnaires, should be moved to the Methodology. They will serve as section 2.8 “Questionnaire Design for map usability and usefulness evaluation”. The rest of section 3.5 could be left in the Results section, as it mostly describes the answers; a more in-depth interpretation already exists in section 4.2 of the Discussion.

L486-569: The authors are basically not discussing the results obtained in relation to those of others, in similar bio-climatic areas or elsewhere.

Thank you for this comment. We will change the text in Sect. 4.1 as follows:

“This methodological approach is consistent with previous wildfire exposure studies that combine burn probability and fire behaviour metrics with the spatial distribution of exposed assets (e.g. Alcasena et al., 2021, 2017; Argañaraz et al., 2017; Haas et al., 2013), but its application to a transboundary Central European landscape remains comparatively rare.”

In Sect. 4.2 we suggest adding the following:

“The observed contrast between BP and FL is also in line with previous wildfire exposure studies, where burn probability is typically interpreted as a likelihood metric and flame length, or conditional flame length, as proxies for potential fire intensity and suppression difficulty (e.g. Alcasena et al., 2017; Sá et al., 2022). The observed relationship between BP and FL partly agrees with previous wildfire exposure studies, but also highlights differences related to the Central European setting of this study. Similarly to Alcasena et al. (2017), BP and FL did not necessarily peak in the same areas: in northern Spain, high BP was linked mainly to fast-spreading herbaceous fuels such as rangelands and cereal crops, whereas the highest Conditional Flame Length values occurred in shrublands and dense forests on slopes aligned with dominant winds. In our study, a comparable decoupling occurs, with some agricultural areas showing high potential FL but low BP due to their limited connection to ignition locations and therefore simulated fire pathways. However, unlike the Mediterranean case studies of Sá et al. (2022) and Alcasena et al. (2021), where shrublands, pine forests, and unmanaged protected areas were major contributors to high intensity or high exposure, high exposure in our study is more strongly shaped by the spatial distribution of ignition clusters, HIZs, wind direction, and cross-border forest structure. This suggests that, in this Central European WUI landscape, exposure depends on local ignition placement, fuel continuity, and the proximity of settlements to simulated fire paths.”

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