Response to Anonymous Reviewer #3

Dear authors,

I was carefully reading the manuscript several times and I found the manuscript well structured and written, with very interesting findings. Indeed, you used very updated and deep literature on the topic and clearly, you added new inputs adapting these fuel maps approach in a European context, being the main gap. However, there are some points that I would like to stress, which could improve the quality of the manuscript. See the comments below:

Response: The authors thank the reviewer for taking the time to review our manuscript. We also appreciate very much the advises and suggestions made. We have thoroughly considered the suggestions made. Improvements have been made in order to improve the quality of the manuscript.

General comments

Introduction

The introduction demonstrated a deep state of the art regarding fuel classification systems, globally and continentally. The review about fuel classification is a great input for other researchers, where the authors put a lot of effort, being a very valuable contribution for future investigations. Well done!

Even though the authors demonstrate a great knowledge and handling of the literature on the subject. The introduction is extremely long and repetitive. From what I understood, subchapters 2.1 and 2.2 are also part of the introduction, or? I would suggest sending these two subchapters as supplementary material, since they are part of a technical report rather than part of a scientific article.

Response: We thank the reviewer for his/her positive comments on the introduction. We are aware that the structure of the manuscript might be a bit complex because the paper has several parts. Introduction is only section 1, not including subchapters 2.1 and 2.2, which refers to the first out of three objectives of the paper: the conceptual development of the new proposed fuel classification system. To clarify and simplify the structure of the whole manuscript, we have unified subchapters 2.1 and 2.2 as "2 Design of the FirEUrisk hierarchical fuel classification system". Moreover, to take into account the reviewer concerns, we shortened the text and deleted some redundant sentences from the Introduction and section 2.

Also, the objectives section in the introduction has been clarified by detailing the workflow in Figure 1 as follows, highlighting the three main parts of the paper:

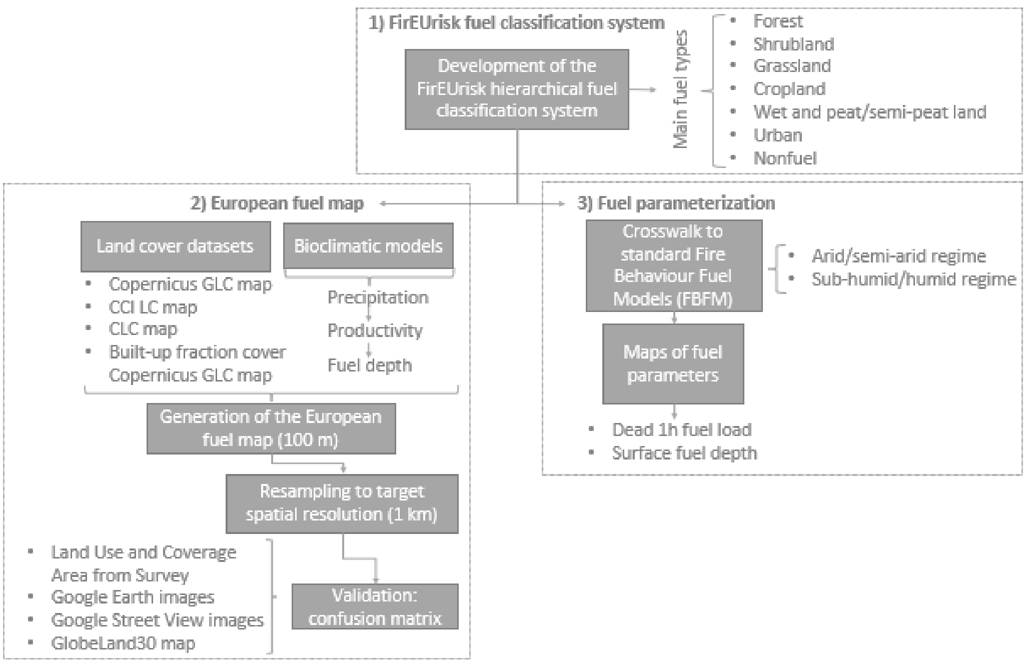

Figure 1. General overview of the structure of this work.

Material and methods

The methodology in general is well addressed. However, I have the following concerns:

- The European fuel classification map that you created to which year belong 2016, 2018, 2019 or 2020? Because it is important to define to which year the map belong independently of the year of publication (article). I would suggest use the oldest layer input to define the year of the European fuel map classification.

Response: The used input land cover datasets for the generation of the European fuel map are the Copernicus GLC map (2019), CCI LC map (2020), CLC map (2018) and Built-up fraction cover Copernicus GLC map (2019). The main used input layer is the Copernicus GLC map (2019), that is why we stablished that our product is circa 2019. This was also added in the text in the data availability section: "**6 Data availability**: The resulting European fuel map (circa 2019, 1 km spatial resolution) in one single-band categorical raster layer in GeoTIFF format is publicly available at https://doi.org/10.21950/YABYCN (Aragoneses et al., 2022a), as well as a Product User Manual (PUM) (Aragoneses et al., 2022b), at *e-cienciaDatos:* https://edatos.consorciomadrono.es/dataset.xhtml?persistentId=doi:10.21950/YABYCN."

References:

Aragoneses, E., Chuvieco, E., and García, M.: Product User Manual for the FirEurisk European fuel map, 1–9 pp., e-cienciaDatos, https://edatos.consorciomadrono.es/dataset.xhtml?persistentId=doi:10.21950/YABYCN, 2022b.

- Why the spatial resolution of the European fuel map classification is 1 km. Considering that most of the input layers used are between 100 and 300 m, I'm not sure why you reprojected the spatial resolution to 1 km. Maybe a reason could be the climate data that you were using from WorldClim2, or? In my opinion, if the main goal is to develop strategies on how handle forest fires at Pan European level the resolution of 1 km is quite wide for this goal.

Response: Although this 1 km resolution might be seen as coarse, it should be noted that the study area is the European continent. The extent of this study area and the available input data makes it difficult to map fuels at a finer scale, especially considering the input data (the CCI LC map at 300 m, the bioclimatic models (including the weather data), etcetera), which led to adopt 1 km as a compromise resolution. It should be considered that the intention to generate a European-scale fuel map is not to simulate fire propagation at regional or local scales, but to have an overview and a holistic perspective of the actual state of fuels in the European territory, that would help to identify areas with higher fire risk conditions and where specific prevention strategies might be adopted to reduce fire risk. In addition, the proposed fuel classification system is hierarchical and multipurpose, referring not only to propagation studies but also to emissions or post-fire recovery, for which 1 km resolution could be a first step to compare fuel and fire risk conditions at a continental scale. Anyway, the classification can be adapted to different spatial scales and in fact, the same legend is being used for Pilot Sites in Europe (regional scales at the FirEUrisk project where the target resolution is 1 Ha or higher), so it has a scalable structure. Nevertheless, similar methods could be developed to map fuel maps at higher resolution for the European scale in future works.

We have added the following to the manuscript in new line 349: "The input layers used for the generation of the European fuel map were previously resampled to 100 m to match the spatial resolution of the Copernicus GLC map, which was our main information source. However, the spatial characteristics of some of the input layers (such as the CCI LC map at 300 m, and the bioclimatic models based on 1 km resolution weather data), recommended to convert the final product to 1 km spatial resolution, which was also the project target resolution for the European scale. Therefore, after obtaining the first fuel type dataset at 100 m resolution, it was resampled to 1 km, carefully accounting for the heterogeneity of European fuel types."

- Regarding the validation, I'm not sure about the validation with another remote sensing input and not through ground truth data for the six main fuel types. However, if you are able to explain well the limitations of this work regarding this gap of information, it can be a valid approach for the two-validation process proposed.

Response: Although ideally validation should be based on field information, it was not feasible to perform an appropriate field validation campaign across Europe. Therefore, validation of the European fuel map was done using four information sources as reference data, from which one is the main source and the rest serve to complement when needed. The main information source, used for the two proposed validations, is LUCAS (Land Use and Coverage Area frame Survey) data from a similar period as the input data (year 2018). This data does not come from remote sensing, but instead they are georeferenced systematic field-surveyed points that allow to identify land cover and land use changes in the European Union including land use forms to fill on the field and photos of the surveyed points. Thus, this information source can be considered as ground truth data. Only when the LUCAS database was not enough to obtain all the information needed for the validation (and only for the second proposed validation), it was complemented with other information sources, namely Google Earth images, Google Street View images and the GlobLand30 map.

This is explained in the methods section in new line 376: "Considering the infeasibility of ground validation of the final product, we first validated the six main fuel types (forest, shrubland, grassland, cropland, wet and peat/semi-peat land, and urban) of our classification, plus the nonfuel category, using LUCAS (Land Use and Coverage Area frame Survey) as reference data. LUCAS points are derived from a field systematic survey, performed every three years by Eurostat to identify land cover and use changes (including photos) in the European Union (Eurostat, 2022a).", and for the second validation: "Since this required a visual interpretation, a 20 % subset of the 5,016 validation points was selected by stratified random sampling. Each point was assigned to a fuel category by visual interpretation of four information sources: 1) the 2018 LUCAS photos at a maximum distance of 200 m, 2) the latest Google Earth images to observe the 1 km^2 pixel, 3) Google Street View images, and 4) the 2020 global land cover GlobeLand30 map (30 m resolution) (Chen and Ban, 2014) with 85.72 % of overall accuracy, based on Landsat and Huanjing (HJ-1) images to help to validate forest and urban covers."

Results

The results are well addressed, but as I mentioned in the methodology section, it is difficult to validate a remote sensing product as a European fuel map classification with other remote sensing inputs. So, my main concern is the lack of field data in the validation. I'm aware of the limitations of the work at this scale. Therefore, these limitations should be properly addressed in the discussion.

Response: The reviewer is right in the fact that we did not visit the field for the validation. However, we did use field data to validate, as explained before. The main information source for validation were LUCAS points and photos, which are a widely used database for land cover mapping.

Discussion

The discussion needs to be addressed more realistic with the results obtained. Again, as I mentioned previously, I have my doubts if this fuel map describes also canopy fuels. Basically, there are two main concerns: i) fuelbed depth is just one variable (basically, the height of the vetegation), but other important attributes as the height at the crown interception and the crown bulk density are missing and ii) I have some doubts about the models that you were using in the fuelbed depth estimation. It is important to clarify this, if the main novelty in this work is the comparison from the previous one at global and European levels, is that these maps only dealt with surface fuels. In my opinion, the canopy fuels are not solved at all through the manuscript. Therefore, I would suggest addressing the discussion about the limitations of this work, that the canopy fuel still is a pending task, but the fuelbed depth is a contribution on it. Also, you can address the discussion on some recommendations on how canopy fuels can be produced in the future through remote sensing.

L110 Into the objectives, the first one is "generating a European advanced fuel classification system to facilitate the integration of continental wildfire risk assessment, including both surface and canopy fuels" I would like to highlight the last point. In my opinion, the canopy fuels are not really addressed within the methodology. It is true that you added the depth fuel (or height of the shrubland, grassland and so on). I have the feeling that canopy fuels is too ambitious according to the methodology and results. The depth fuel can partially be an input in the canopy fuels. However, other important metrics to understand better the canopy fuels are missing, such as crown base height, crown bulk density, among others. Therefore, I would suggest being more focused on surface fuels, which is most of the work done through the manuscript.

Response: Regarding the comment on the results and the one for L110, we understand the reviewer's point, as there are some missing fuel parameters referring to canopy fuels, such as crown base height or crown bulk density. In this paper, we focus on the description of the legend of the proposed fuel classification system and mapping, and a first possibility to parameterize surface fuels using standard surface fuel models; and future works will focus on the parameterization of both canopy and surface fuels. Here, we mapped fuel types and fuelbed depth, which helps to identify fuel types that only differ in height. Some of the variables the reviewer proposes refer to fuel parameters, and this is subject of our on-going research Moreover, the proposed fuel typology includes different forest types because we understand that they present different canopy behaviour and, although their canopy parameters are not yet estimated, the fuel divisions are thought because they affect canopy fuels.

To clarify that there are canopy fuel parameters still missing, the objectives in new line 104 were modified as: "The first one was generating a fuel classification system to facilitate the integration of continental wildfire risk assessment, including both surface and canopy fuel types", and the following was added to the discussion in new line 716: "The full surface fuel set information needed to run fire propagation models can be extracted from the crosswalk to the FBFM, complemented with other canopy fuel parameters (such as crown base height or crown bulk density) and other necessary input data (e.g., weather conditions, topography, ignitions, etcetera) to run fire spread models (e.g., FlamMap (Finney, 2006) and FARSITE (Finney, 2004), as embedded in FlamMap 6.2 (https://www.firelab.org/project/flammap)."

Regarding the recommendations on how canopy fuels can be produced in the future through remote sensing, the discussion was completed with this in new line 720: "This should be subject of an extension of this paper and could be based on the calibration of models that estimate canopy fuel parameters using airborne and satellite LiDAR systems, for which regional airborne LiDAR would be key to consider the heterogeneity of European fuels before using the global satellite LiDAR data for the continental scale". Indeed, the authors are currently working on that, which is planned to be the next step in their research.

About the models used to derive the surface fuel heights, the discussion was modified to give a more realistic view of the results in new line 605: "Estimating shrubland and grassland fuelbed depth was challenging. To the best of our knowledge, there are no large-scale reliable datasets in Europe on these variables, which is limiting to our purposes. However, despite the models chosen to estimate surface fuelbed depth were not specifically developed for European areas, the biogeographical similarity of the regions for which they were developed to European conditions make them acceptable for our purposes."

Conclusions

The conclusions should be rewrite according to the previous suggestion and clearly define the novelty of the work compering to the previous one according to the limitations implied by a map at the European level. In short, the manuscript is a valuable contribution, but need to be improved before to be published according to the comments and suggestions provided.

Response: The conclusions were rewritten to:

1) Specify that the classification refers to both surface and canopy categories, but that the parameterization only referred to surface fuels.
2) Highlight the novelty aspects of the work.
3) Emphasize the limitations of the work, most of them related to the European level (size and complexity of the study area).

The conclusions are now as follows: "This paper, developed in the framework of the European FirEUrisk project, presents a new hierarchical fuel classification system for surface and canopy fuels adapted to the European conditions, as well as methods to map those categories and assign them fuel parameters. The final European fuel map contains 20 fuel types, including both surface and canopy fuel types. The estimated overall accuracy was 88 % for the main fuel types and 81 % for all mapped fuel types. Finally, the paper shows an example of a crosswalk between the proposed fuel types and standard fuel models, in this case the Fire Behaviour Fuel Models (FBFM) (Scott and Burgan, 2005), that provides a full set of surface fuel parameters useful for surface fire behaviour modelling. Our approach, based on expert knowledge, GIS, existing land cover datasets, biogeographic data, and bioclimatic modelling, could be readily applied to other regions.

The results of this study constitute the first step towards a risk-wise landscape and fuel mapping development across Europe, which will help integrated, strategic, coherent, and comprehensive decision making for fire risk prevention, assessment, and evaluation. The results have wide applicability because they meet the actual unfulfilled fuel mapping needs in Europe: 1) the development of a fuel classification system specifically designed for European conditions, which allows not to rely on external classifications that should be only applied to the regions for which they were developed, 2) enabling coordination, integrating fuel mapping at different spatial scales and across European regions through a common fuel legend with hierarchical levels, 3) multipurpose, including prevention, propagation, behaviour, emissions, and suppression, 4) mapping fuel types not previously considered at European scale that are key for protecting people and the environment from the devastating effects of fires: forest canopy fuels (key for crown and extreme fires), wet and peat/semi-peat land fuels (key for emissions) and urban fuels in the Wildland Urban Interface (key for people's and socio-economic safety), 5) the generation of an updated European-specific fuel map, compared to the EFFIS fuel map from year 2000 (European Forest Fire Information System (EFFIS), 2017), and 6) the preliminary surface fuel parameterization for Europe that can be used for estimating fuel parameters whenever there is no suitable input data available. Overall, the existence of updated land cover datasets and bioclimatic models for the European territory is limiting, and work is still needed to parameterize canopy fuels. The results of this work are part of the new FirEUrisk integrated three-part perspective of fire risk, whose strategy is meant to shift the thinking of wildfire management by looking simultaneously to fire assessment, reduction, and adaptation from a common scheme."

Specific comments

L20 In the abstract, you mentioned that the main fuel categories were grouped into six land uses, but I'm not sure why you included urban category, are you expecting forest fires into urban parks, or?

Response: Our proposed fuel classification system has the novelty of considering urban fuels, defined in this paper as those fuels in the intermix or interface of built-up areas, i.e. the Wildland Urban Interface (WUI). This constitutes an interesting improvement compared to pre-existing fuel classification systems where WUI areas are not considered fuels and therefore, are not parameterized (case of FBFM). Understanding urban fuels allows to assess residential and non-natural fuels, which can help to prevent fire risk to affecting human settlements and lives, and socio-economic losses (Bowman et al., 2017, 2020).

To clarify why urban fuels are included in the proposed classification, we have added the following to:

- New line 161: "Urban: areas with ≥ 15 % built-up structures and/or buildings. The standard CLC division between continuous and discontinuous fabric was followed, related to the amount of vegetation belonging to the intermix and interface of the Wildland-Urban Interface (WUI). This is part of the innovation of the proposed classification system, as it allows the assessment of residential and non-natural fuels, which can in turn help identifying anthropic areas where fires can affect human settlements and lives.",
- New line 568: "In addition, the FirEurisk fuel map includes new categories such as wet and peat/semi-peat land fuel types, which are key to understand fire emissions; and urban fuel types, crucial to prevent fire affecting humans, which were not considered in previous continental and global fuel maps.",
- New line 627: "Urban fuel types are the least represented in Europe, but they are the most dangerous from an economic, societal and human health point of view (Bowman et al., 2011). Mapping urban fuel types represents an advance of the proposed classification system, as it allows the assessment of residential and non-natural fuels, which can in turn help identifying anthropic areas where fires can affect human settlements and lives.",
- New line 770: "…4) mapping fuel types not previously considered at European scale that are key for protecting people and the environment from the devastating effects of fires: forest canopy fuels (key for crown and extreme fires), wet and peat/semi-peat land fuels (key for emissions) and urban fuels in the Wildland Urban Interface (key for people's and socio-economic safety)…".

References:
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L145 You defined the vegetation height as fuel depth, but I'm not sure if this term is correct, maybe "fuel height"?

Response: Here we are referring to the fuelbed depth, which is associated to surface fuels. We have changed "fuel depth" by "fuelbed depth" in the text to indicate that we are referring to surface fuels, including shrubland and grassland. This terminology is largely accepted (see https://www.nwcg.gov/term/glossary/fuel-bed-depth). Also, this was clarified the first time the term appears in the text in new line 175: "For shrubland and grassland fuel types, subcategories were created based on fuelbed depth (height of the surface fuel layer)."

L160 Garrigue and maquis are just terms used in different countries, but with the same meaning "shrubland". I would suggest deleting these terms because is repetitive or explain that is a specific term according to a specific country.

Response: According to the reviewer's suggestion, the two terms were deleted from the definition of shrubland.

L195 Since the article probably will be published in 2023, it could be important also highlight the recent forest fire between the Czech Republic and Germany in 2022 and how the forest fires are going more up in latitude.

Response: As suggested by the reviewer, this information was added in new line 194: "However, a recent increase in fire activity in higher latitudes has been observed: e.g., fires in Sweden in 2018 (San-Miguel-Ayanz et al., 2021), and the fire between the Czech Republic and Germany in 2022 (Global Disaster Alert and Coordination system, 2022)."

References:
Global Disaster Alert and Coordination system: Forest Fire (2287 ha) in Germany, Czech Republic 24 Jul 2022, 2022, https://www.gdacs.org/report.aspx?eventtype=WF&eventid=1007792, last access 18 November 2022.

L230 It is not clear at all to me how the fuel height was determined and how accurate it was considering that the units are in centimetres, which is hard to handle from earth observation data (and models). Are some ground truth data available to validate the fuelbed depth?

Response: The fuel height was estimated using the bioclimatic models.

Regarding the first part of the comment, the authors are aware that the estimation in centimetres can be tricky, and its accuracy is limited. That is why the proposed classification and the final fuel map aggregate the fuel types in three groups: high, medium, and low fuelbed depth, not giving specific heights in cm.

Regarding the second part of the comment, these models are already calibrated and validated, and their details can be read in the papers where they were originally presented. However, the authors also validated the results of their application in the validation section of the fuel map (by using the LUCAS photos). LUCAS photos do not come from remote sensing but are a field survey, as explained before, which is believed to serve for our validation purposes. However, the authors are aware about the limitations of estimating and validating fuelbed depth because of its high temporal variability. This is the reason why the bioclimatic models refer to the potential fuelbed depth. Also, this has been highlighted in the discussion in new line 678: "Shrubland and grassland fuel types' errors are significant, mostly between fuelbed depth categories. Therefore, care must be taken for these results, as estimating fuelbed depth from photos is challenging, and fuelbed depth varies with time. These limitations specially affect grassland due to its low depth, rapid growth, and that high grassland is frequently cut. Thus, grassland fuelbed depth is very changeable so we assume the European fuel map may only be accurate for some periods of the year. We validated the proposed fuel map considering the mean potential fuelbed depth."

L245 Considering that the map layers are from different years (e.g., Copernicus GLC map 2019, CCI LC map 2020, etc.) I would suggest adding the years when the layers were created in the workflow of the figure 3.

Response: Done. The new Figure is as follows:

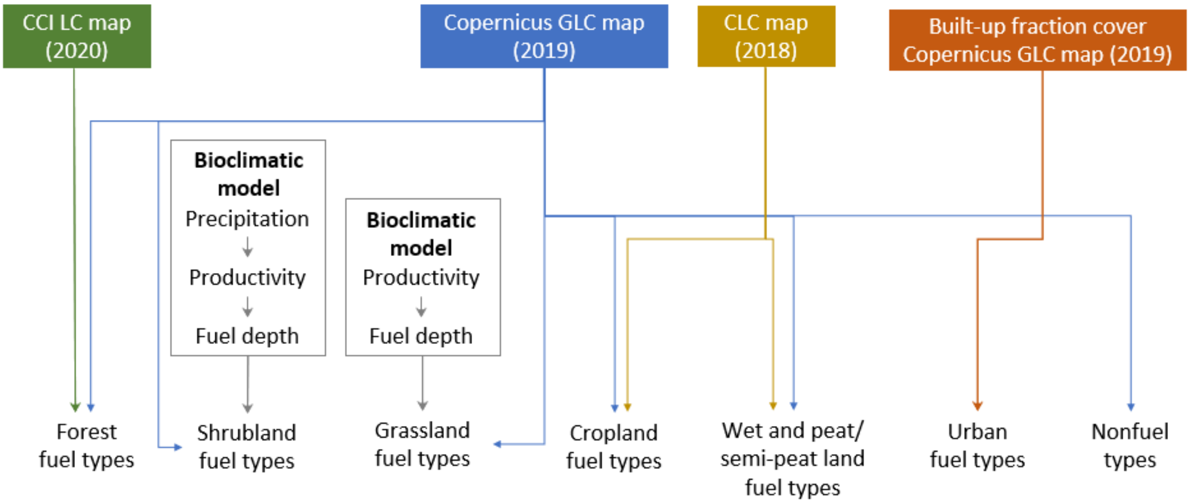

Figure 3. Methodology used to generate the European fuel map. The input sources are in the text.

L290 Where the biomass data is coming from to feed the depth (m) response variable? I have my doubts about the models, especially in its validation (see comment in L230). The same concern is in equation 3.

Response: The biomass data used in equation 2 is calculated in equation 1. For shrubland, this is a two-steps model: first, Mean Annual Precipitation (MAP) data is used to estimate biomass; second, the estimated biomass is used to estimate the potential fuelbed height. The reasoning behind this model is that shrubland depth is directly related to shrubland productivity (Radloff and Mucina, 2007; Saglam et al., 2008; Ali et al., 2015), which is mainly determined by the Mean Annual Precipitation (MAP) (Shoshany and Karnibad, 2015; Paradis et al., 2016; Bohlman et al., 2018; Zhang et al., 2018b) through biomass accumulation (Keeley and Keeley, 1977; Schlesinger and Gill, 1980; Gray and Schlesinger, 1981; Bohlman et al., 2018).

For grassland, the model has only one step: grassland fuelbed depth was directly estimated from grassland biomass data. Again, the reasoning behind this is that grassland depth is directly related to grassland productivity or biomass (Zhang et al., 2018a; Crabbe et al., 2019; Michez et al., 2019; Batistoti et al., 2019). For this case, we directly used already-existing information on mean grassland biomass for European zones based on consistent inventory of regional statistics on this variable (Smit et al., 2008).

References:

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Zhang, X., Guan, T., Zhou, J., Cai, W., Gao, N., Du, H., Jiang, L., Lai, L., and Zheng, Y.: Community Characteristics and Leaf Stoichiometric Traits of Desert Ecosystems Regulated by Precipitation and Soil in an Arid Area of China, Int. J. Environ. Res. Public Health, 15 (1), 109, https://doi.org/10.3390/IJERPH15010109, 2018b.

L420 The histogram showed shrubs up to 6 m. I believe that there is a misunderstanding in the definition between what is a tree and what is a shrub. Probably, in the distribution that the histogram is showing, there are some trees included.

Response: The following in new line 430 was added and is self-explicative: “Although shrubland are generally considered up to 5 m, exceptions are allowed subject to the plant’s physiognomic aspect (Food and Agriculture Organization, 2000). Therefore, here we allowed for plants higher to 5 m being classified as shrubland if they have a clear physiognomic aspect of shrub.”

L455 The table 4 is quite large and the same information is repeated in the text. Maybe, it would be better to replace the table by pie graphs or send as supplementary material.

L525 I would suggest the same that in L455, the table 8 is quite large and could be more suitable transform in a pie graph only the % values.

Response: Following the reviewer’s suggestion, Tables 4 and 8 were sent to Appendices. Pie graphs were not included as they were considered to be repetitive with the information already provided in the paper: Tables in the Appendix, fuel maps and description in the text.

L545 Figure 7 is connected to figure 4? Because the results are completely different but is the same attributed measured. Or?

Response: These two figures show different things. On one hand, Figure 4 represents the fuelbed dept for every shrubland and grassland pixel after applying the bioclimatic models. These pixels where then aggregated into the three height groups (high, medium, and low) according to the proposed thresholds, resulting in part of Figure 5. On the other hand, Figure 7 is the result of applying the crosswalk from the proposed fuel types to the FBFM models. Each of the FBFM models has already-defined fuel parameters, which can be mapped after applying the crosswalk to the European territory. In this sense, Figure 7 shows an example of mapped parameters from the application of the crosswalk. The fuelbed depth in this last case refers only to surface fuels and refers to it in shrubland, grassland and forest environments, whereas Figure 4 only refers to the pixels identified as shrubland and grassland in the European fuel map for the FirEUrisk fuel classification system.

To clarify this in the text, some modifications have been done:

"**Figure 4.** Histograms for shrubland and grassland fuelbed depth (m) in Europe obtained from the application of the bioclimatic models. The blue lines represent the fuelbed depth threshold used to subdivide shrubland and grassland fuel types."

"**Figure 7.** Surface dead 1h fuel load and fuelbed depth over Europe obtained from the crosswalk from the FirEUrisk fuel types to the FBFM models. Note that surface fuelbed depth for the forest fuels refers to the understory, not the crowns."

Please, find also attached the new version of the manuscript with the changes done.