Response to the referee #1 for the manuscript:
Varying relationships between fire radiative power and fire size at global scale

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Answer to reviewer #1

Major concerns:

I) The first is that the study is based on the GFED regions but then wants to interpret differences between the regions to be driven by biomass availability and drought. If you want to understand whether differences are driven by biomass and drought then a much more straight forward way to analyse the data would be to group them according to biomass and drought, not according to the GFED regions that average over all Northern Hemisphere Africa, which contains the whole gradient from desert with low biomass and strong drought to tropical rainforest with no drought and high biomass. I am very confident that the results could be much clearer and support your conclusions much better if the study design was rearranged to directly look at the effects of drought and biomass on these relationships, by grouping the data according to these two parameters.
Answer: We agree that relying only on GFED regions tends to mix together biomes with different biomass, fuel types, and with very different drought conditions. The problem with the use of drought datasets is that it is difficult to choose how to perform the separation between different levels of 'drought severity' : we could focus on the length of the drought season, or the severity of the Fire Danger Index, a combination of both, etc .... This choice would seem quite arbitrary, and would require a dedicated analysis. Instead, we propose to use MODIS Land Cover Data to separate each GFED regions in different biomes (Forested, (green) Savannas (light green), Grasslands/Shrublands (orange), see Figure attached to the answer). We clearly see that the relationship varies with the biomes : the results are especially striking in Australia, where we see that the FRP/FS relationship differs a lot depending on the considered biome. Finally, since we do not directly study the relationship with biomass and drought, we removed from the abstract and the discussion the sentences where we claimed that the fire intensity was driven by these quantities.

Separating our analysis depending on land cover is also important regarding the second major concern that you have raised (and that has also been raised by the other reviewers). We considered that FRP could be used as a proxy of the fire reaction intensity in the flaming front, but we did not discuss the limitations of such an approach. Particularly, we realized that the reliability of this hypothesis strongly depends on the land cover : for grassland, most of the energy is released in the flaming front, whereas for forested areas, radiation from smouldering fires also contribute to FRP. Therefore, the separation into land cover also appears very natural, and we can now discuss the hypothesis 'FRP is a proxy of fire intensity' and the reliability of the results depending on the considered land cover.

Note that what we suggest here is a 'double' separation (GFED and Land Cover). We think that keeping the separation into GFED regions (and separating each of them into different Land Cover) is important for two reasons :
- They define regions which are widely used within the fire community
- Grouping all fires belonging to a given biome without separating in GFED regions would mix together regions with different fire practices/policy/management

II) The second is that the manuscript needs a discussion of reliability of the data, especially for the fire intensity. There are a number of limitations on the observability of fire radiative power. The point that there are still these clear spatial and temporal patterns in my opinion indicate that there is useful information in the dataset, however the problems associated with the dataset should be mentioned and discussed. For instance the energy observed is the energy released in one pixel, this energy might come from a very intense fire covering a small part or a low intensity fire covering large part of the grid cell. The observation of fire intensity strongly depends on the scan angle. Moreover fire intensity has a diurnal cycle and peak fire intensity might differ between the biomes. The satellite overpass might happen at the peak time in some grid cells but not in others. Vegetation structure influences what the satellite can observe, intensity of sub-canopy fires will certainly be underestimated. I am not an expert in remote sensing, but I think that such issues need to be mentioned to provide a balanced discussion of the results.

Answer: A discussion on the data reliability was clearly missing. We realized that we did not defined well-enough what we meant by "fire intensity", and how does this relate to FRP. Moreover, we did not discuss or reference the spatial and temporal sampling error that might impact the measurements of FRP. We plan to do the following changes in the manuscript :

- First, we would like to replace in the text 'Fire Intensity' by 'Fire Radiative Power'. What we observe is FRP, and then we interpret it as a proxy of fire reaction intensity. We would also like to change the title of the article into : 'Varying relationships between fire radiative power and fire size at global scale' if the editor agrees.

- Second, we will provide a dedicated section in the discussion (with references) to thoroughly discuss these issues. Note that the separation into land cover strongly helps to discuss the reliability of FRP as a proxy of fire reaction intensity, since this is expected to depend on Land Cover. Here comes a draft of the dedicated discussion:

"In the previous section, we hypothesised that FRP could be used as a proxy of fire reaction intensity. We now focus on the limitations of such an approach. First, the energy released by a wildfire can be decomposed in three parts : convection, conduction, and radiation. FRP only represents the radiative part of the energy emitted by a fire. Moreover, the fire reaction intensity used in Rothermel's equation does not share the same spatial extent as FRP : fire reaction intensity pertains to the flaming front of the fire, while FRP integrates all the radiative energy emitted over a 1 km^2 window. This means that radiation emitted from smouldering can also contribute to FRP, not only the flaming front. The impact should differ for different vegetation types : smouldering fires are more frequent in forested areas, whereas in grasslands most of the detected radiative power will be released by the active fire front. Another issue appears from the integration of radiative energy over the 1 km^2 window : it is impossible to know if the detected FRP arises only from a fire covering the full 1 km^2 area or only from a smaller fraction of the FRP pixel. However, we can expect this effect to be mitigated by the fact that our analysis does not account for very small fires, since the FRY database does not provide fire patches smaller than 107 ha for MCD64A1. Finally, a recent study (Roberts et al. 2018) used 3D radiative transfer simulations to show that the canopy structure intercepts part of the FRP emitted by surface fires. This means that the FRP measured from remote sensing for forested areas and savannas could underestimate the real FRP. We can also expect this underestimation to vary with tree species. For example, it is probable that the amount of radiation energy intercepted by the canopy differs strongly between canopy fires from highly flammable black pines from BONA (Rogers et al. 2015) and surface fires from pine needle bed in BOAS. All these considerations emphasize the importance to split the study of the relationship between fire size and FRP in different vegetation types, since the reliability of using FRP as a proxy of fire reaction intensity depends on it."

"The amount of radiative energy reaching the MODIS instruments is much smaller at large scan angles than at Nadir. This means that the MODIS instruments will be less sensitive to low values of FRP at high latitude (Giglio et al. 2003, Schröder et al. 2005). This could explain the difference of the distribution of FRP associated with fire patches in BONA (Figure 2) : the stronger asymmetry

of the distribution in this region (i.e. the larger tail toward high FRP values) could arise from missing active fire data from less intense fires in this region. The temporal sampling of FRP also differs with the latitudinal coordinate : the number of satellite overpass is larger at high latitude than at the equator (from 2 observations per day until 15 at the poles, Giglio et al. 2006). This should rise the probability to recover FRP information for fire patches at high latitude, assuming that their radiative intensity is high enough to exceed the higher detection threshold at larger scan angles. Also, in some regions (such as NHAF and SHAF) fires exhibit a strong diurnal cycle (Giglio et al. 2006). The detection rate of active fires will therefore be higher if the peak of diurnal intensity is synchronized with satellite overpass. However, we can expect the sampling error rate and the variation of FRP sensitivity with latitude to be more homogeneous within each GFED regions that at global scale."

Please find our point-by-point answers to specific comments in the following.

1) l.17: thresholds differ between regions: what defines the regions? climate, humans, vegetation types?
Answer: We meant GFED regions. As stated in our main answer to the review, we also separate each GFED regions in different biomes (see Figure 3).
We have added in the abstract that the relationship changes with the region and the considered vegetation type.

2) l. 20: seasonal effects, could there be an influence of anthropogenic fire use too? Percolation theory explains why fires are most intense or why fires are smaller in the late season? I guess the latter.
Answer: Yes. For example, in the discussion (l. 252), we mention the use of prescribed burning at the beginning of the fire season in Africa to limit fire size. Concerning the percolation theory, the sentence in the abstract was not clear enough. Indeed, the term "this effect" was referring to the decrease of fire size toward the end of the season.
We have modified the text to make it clearer.

3) l. 25-27: not sure I agree 100% with the reasoning: fire models have been included before in DGVMs, for instance Arora and Boer (2005). I think the reason was more the strong impact on vegetation and overestimation of tree cover in savannas in many DGVMs.
Answer: We agree. We removed 'As a result' from the sentence.

4) l. 28: prediction of vegetation dynamics and the carbon cycle.
Answer: The text has been changed.

5) l 47: also the impact of fire varies with the size, the fire size characteristics therefore could be more informative than only burned area.
Answer: Yes, we agree that the shape of the fire can have an effect on its impact on the vegetation.
We have added a couple of references (Greene et al. 2005, Cary et al. 2009), and we have added a sentence in the text to mention this effect.

6) l. 52: maybe drivers of propagation and ignition are not driven by the same climate variables, but the fraction of ignitions turning into fires is determined by similar drivers, burned area and fire counts therefore have quite similar spatial patterns.
Answer: We agree, but in this paragraph, we do not discuss/compare Burned Area to fire counts. We just stated that separating ignitions from propagation would bring more information than just using BA or fire counts. However, this comment is related to comment

14 (where we actually compared fire counts and fire ignition), which brought some modification in the manuscript.

7) l.57: is it fire intensity of fire line intensity? and based on the equations this is not expected for large fire size? or do you mean the Rothermel equations were only tested for small scale (laboratory to stand scale) and it is unclear whether the equations hold true for larger scales (not for larger fires).
Answer: Actually, this is reaction intensity of the fire front. We meant that Rothermel's equation was only tested at local scale, as stated at l. 38-39.
We have modified the text to recall this on l. 57.

8) l. 95: explain the difference between fire intensity and fire radiative power.
Answer: We will provide a more accurate definition of fire (reaction) intensity and fire radiative power when the terms are introduced in the manuscripts (i.e., at line 57 for fire intensity and line 85 for FRP). Following the received comments, we have decided to focus on FRP throughout the presentation of the results, and introduced the use of FRP as proxy of FI in the interpretation of the result only. The limitation of this hypothesis is discussed in the discussion section.
We added also some references on the use of FRP as a proxy for several fire severity applications to justify the use of this index in our analysis:
-field work to etimate fire intensity on fire severity and impact on soil: Barret & kasischke 2013, Sparks et al. 2018 (in biogeosciences).
-fire risk modelling of fire size and intensity based on FRP: Hernandez et al. (2015)
-biomass combustion rates from FRP in Africa: Roberts et al. (2005)
-relating a fire spread equation (Byram) to fire intensity from infrared remote sensing: Johnson et al. (2017)

9) l. 96: are there any spatial or temporal patterns in the the discarded fire patches ? This might indicate biases in the FRP detection.
Answer: Yes, there are some spatial patterns. We now discuss this in the methodology and discussion section, and we have added a couple of supplementary plots with :
- a map of the ratio of missed matches between fire patches and active fire pixel data.
- a histogram showing the global fire size distribution of fire patches and the distribution of fire patches without recovered active fire information.

10) l.110: text says median, figure caption says mean. The figure could also include a burned area map to show that the patterns are different, between the characteristics.
Answer: This was a typo. We have added a map of yearly burned area over the same type period as MCD64A1, and briefly discuss the difference with fire count in the text.

11) l.112: patterns of size and FRP look not so similar to me.
Answer: We have modified the text, and try to provide a more accurate description of the figure.

12) l. 117: use either mean or average.
Answer: This was a typo. We kept 'average'.

13) l.119: could this peak simply be because lower intensity is simply not detected by the satellite. What is the explanation for this peak at intermediate fire intensities?
Answer: Thresholds of FRP detection vary between 9 and 11 MW (Schroeder et al. 2010, Roberts and Wooster 2008) for MOD14 and MYD14, below which no data are available. In turn, remotely sensed finer resolution analysis actually concluded that MOD14 may

underestimate by 20% captured fire pixels, particularly for small fires (Wooster et al. 2012, Peterson et al. 2013). Beside spatial resolution, different sensors can differentially capture FRP (Li et al. 2018) due to solar angle and vegetation types. The 9-11MW threshold falls in the 1st bin of FRP in Figure 2, and could therefore explain the peak at intermediate FRP.
We are now discussing this in the manuscript (in the result and discussion section), and we have added the aforementioned references.

14) l.121: change "number individual.." to " number of individual..." I assume fire counts is related more closely to burned area as two counts could be individual fires or the same fire, so some differences are also expected.
Answer: We agree that active fire counts are closer to burn area than individual number of fire patches. We removed the sentence from the text.

15) l.124: It would be useful to consistently use FI or FRP, now it is FI in the text and FRP in the figure.
Answer: Following the comments of the reviewers, we choose to use FRP throughout the text. We agree that we interpret FRP as a proxy of FI, not directly as FI itself. Moreover, we added a paragraph in the discussion about the differences between reaction intensity and FRP (see our main answer).

16) l. 125-28: I don't see that the fire size is clearly decreasing. it is a bit tempting also to interpret the error bars as error bars. Maybe having three lines for 25th percentile, median 75th percentile could avoid that misunderstanding. Probably showing the 4th order polynomial with uncertainty bands could give a better impression whether decreases and maximum are robust. My confidence based on the plots shown is rather low, and now these threshold become quite important for the following discussion. Showing some kind of robustness and uncertainty on this threshold would therefore be important.
Answer: The problem with lines is that it makes it difficult to represent the burn date information encoded with the dot/colorbar color, which is an important information for the discussion. We prefer to keep the plot as it is now. However we have added the interpolated polynomial "under" the dot, to show the humped relationship of the median fire size wrt FRP. Also, please note that the large range of fire size (due to the 75th quantiles, 5 to 10 times bigger to median fire size) render difficult the sight of the decrease after the threshold is reached.
We also realized that the description of our methodology was not accurate enough. First, we only fit the median value of FRP, not the total distribution. The polynomial fit is only used to smooth the maximum median FRP value from the FRP vs FS relationship. We then perform two linear regression : one in the range [FRP > 0, FRP < FRP_{max}], one in the range [FRP > FRP_{max}, FRP < 300]. We obtain uncertainties (with their correlation) on each of the 5 parameters of the polynomial fit, and the uncertainty on the each slope of the linear regression. The uncertainty on the parameters of the polynomial are low (less than 1% in terms of relative uncertainties for all parameters).
Similarly, the relative error on the slope fitted over the range [FRP > FRP_{max}, FRP < 300] is lower than 1%.

17) l. 174: higher FI threshold for forests: can this be explained by Rothermel?
Answer: Rothermel only explains the expected linear relationship between fire size and fire intensity. A higher FRP threshold simply means that Rothermel s equation is valid on a larger range of FRP, and we suggest that this could arise from the fuel array continuity.

18) l. 176-7: Rothermel also uses different parameters for different vegetation types and fuel moisture and is able to reproduce the varying constraint hypothesis.

Answer: Yes, Rothermel is able to simulate the varying constraint hypothesis. but we show that Rothermel is no more valid (or highly affected by another factor; potentially landscape fuel continuity) for high intensity fires. For example, late fire season in Africa is dry and not fuel-limited so this season should experience the highest FS as a function of FI.
We believe this paragraph is not fully related to our results, so, for clarity of the manuscript and regarding the comment of the reviewer, we removed the paragraph concerning this comment.

19) l.185: GFED regions are not biomes
Answer: This is true. We have now separated each GFED regions in different biomes using Land Cover data from MODIS. See our main answer to the review.

20) l.195: so you expect a lower threshold for higher fragmentation? is that what you find in your analysis?
Answer: We fully rephrased and developed this sentence. We mention here that landscapes can be intrinsically fragmented (by roads, or cropland mosaic), and seasonally fragmented by successive fires. In turn, successive fires can interact at the landscape scale, so the edge of the first fire acts as a barrier for the second fire propagation (Teske et al. 2012). In savannas, patchy mosaics of burned land are then intentionnaly created early in the fire season as a preventative strategy for large fires emerging later in the season (Laris et al. 2002). This sentence is part of the discussion and we propose here an hypothesis on our findings of the FS/FRP threshold.

21) l.215: I would expect a very high fragmentation in EURO and TENA (lots of big streets) and strongly managed, which is why fire models usually overestimate burned area there. Is this only meant for interpreting the seasonality? so no fragmentation due to burning?
Answer: In these regions, despite being highly populated and urbanized, burned area has been shown to be mostly driven by weather and anthropogenic process rather than landscape fragmentation (cf figure 9 in Le Page et al. (2015)), a result supported by our findings. We added this reference in the manuscript.

22) l.220: not all the tropics has rainfall all year long.
Answer: We agree. We have changed the text to 'where drought period are shorter'

23) l. 221: are you suggesting that the savanna species suppress fire? burned are is much higher in savannas than in TENA and BOAS. I don't understand the logic here.
Answer: We are speaking about propagation once a fire has started. Our results show that fires are larger in forests of TENA/BONA than in savannas. However the number of individual fire patches is much lower in TENA/BONA, which results in a lower burn area.
In BONA/TENA, once a fire has started (mostly on the ground layer), they turn into crown fires which are hardly controlled, while grassland fires can be more easily stopped by changes in weather or landscape obstacles.
We rephrased the sentence in the manuscript:
'They can therefore propagate further than ground fire and fire resistant species found in savannas and woodlands in semi-arid tropical regions'
=> 'they can therefore propagate further than herbaceous fires hardly turning into crown fires in savannas and woodlands in semi arid tropical regions.'

24) l. 223: vegetation is less flammable where?
Answer: In BOAS. We have modified the text.

25) l. 237: FDI increased everywhere?

Answer: Rather than FDI, the article actually focus on fire season length. This has been obsereved in some regions only. We have changed the text.

26) l.251: agricultural expansion leads to a reduction of burnable area. why? Croplands are burned, pastures are burned. Also the more fragmented landscape, is there a study showing that the landscape is more fragmented. I is an assumption in models and to explain the decline in burned area. Give a reference where this fragmentation is observed, or identify it as a common assumption. Could this be an effect of having smaller fires in croplands and therefore the detectable burned area is declining, not the burned area itself?

Answer: We now provide in the manuscript some references illustrating the fragmentation of landscapes in savannas worldwide :

- Sulieman, HM. 2018. Exploring drivers of forest degradation and fragmentation in sudan: the case of Erawashda forest and its surrounding community. Science of the total environment. 621: 895-904.

- Oliveira SN, de Carvalho OA, Gomes RAT, Guimaraes RF, McManus CM. 2017. Landscape-fragmentation change due to recent agricultural expansion in the Brazilian Savanna, Western Bahia, Brazil. regional environmental change 17(2): 411-423

- Kamusoko C., Aniya M. 2007. Land use/cover change and landscape fragmentation analysis in the Bindura District, Zimbabwe . Land degradation and development 18(2): 221-223

27) l. 259: BA saturates toward the end of the drought season: is this really reproduced by models? Any reference?

Answer: We did not find any references about this, but this mechanism looks realistic in regions with high BA (NHAF/SHAF) looking at the equations from Thonicke et al. We rephrase the sentence :

"Because of the reduction of the available fuel load due to burning by preceding fires, we can expect than BA saturates toward the end of the drought season in DGVMs."

28) l. 267: fire-prone ecosystems: actually you didn't group the analysis by ecosystmes, for the tropical regions you group everything together, tropical rainforest and savannas are not separated. I think it would be smarter to group the data for this analysis based on vegetation and climatic parameters not by geographical regions. grouping high and low tree density together could confound the results.

Answer: We agree. See our main answer to the reviewer's comment.

29) l. 271: FI threshold is driven by biomass and drought severity: Most of the regions have a strong variation of biomass and drought severity. It therefore would be better to use drought severity and biomass to group the data.

Answer: See main answer to the reviewer's comment. We suggest to divide each region depending on their land cover.

Answer to reviewer #2

Major concerns:

This manuscript is interesting and fit well with the focuses of BG. It can be published after a careful revision. I am not a fire ecologist. Consequently, I met a lot of difficulties in understanding concepts, variables names and their definitions you used in the manuscript. The guiding principle of your analysis is the Rothermel (1972)'s fire spread model ("Rothermel's equation" line 35, "Following the hypothesis from Rothermel's equation of fire spread" line 170). It is a very detailed local scale model. It is one of the most used models to simulate the forward rate of spread at the front of a surface fire, and is the primary fire spread model applied in many fire prediction systems. In the Rothermel's model, rate of spread is simulated as a function of topography, microclimate conditions and a fire behavior fuel model or fuel model that consists of numerous parameters for a given fuel complex. Standard fuel models have often been shown inappropriate for representing local conditions. In this manuscript, you referred to the Rothermel (1972)'s equation. In the original USDA paper, the number of equations was c.a. 90. It will be fine that in your up-scaling procedure, from local to global, you explain how you summarized the Rothermel (1972)'s fire spread model for finally analyze the relationship between fire patch area and fire intensity. A short explanation will be useful and will clarify the discussion in which you mixed: fuel biomass availability, biomass gradient, moisture content of the fuel, fragmentation, wind speed, fuel bulk density, fuel load, etc.

Answer: Looking at your review and the reviews from the two other referees, we realized that we did not defined well the different quantities that we are using throughout the article : fire (reaction) intensity, FRP, and how they relate to Rothermel's equation. We are now giving a more careful definition of all terms. Concerning Rothermel's equation, we are using the "main" equation for Rate of Spead, which is used in most fire module : this is equation (10) in the Rothermel (1972) article. We will clarify this in our revision, because our description is not straightforward for anybody without a fire ecologist background.
Also, note that following the suggestions from all referees, we decided to change "Fire Intensity" with "Fire Radiative Power" in the title and throughout the article. We are looking at relationships between fire size and FRP, and then we interpret FRP as a proxy of FI.

My second main concern is your cutting of continents by using the one proposed by the GFED. The 14 regions are very arbitrary. As an example EURO includes the surrounding of the northern part of the Mediterranean Sea where the fire regime surely doesn't follow the same pattern than in more Northern regions. Likely using a more "ecologically-based" or "climatically-related" cutting will yield contrasted results?

Answer: Yes, this was a request from the three reviewers.

Splitting the data following drought is difficult, because there are plenty numerous possibilities to perform the split (using the length of the season ? The intensity of the drought index ? A combination of both ?). We suggest to split each GFED regions using MODIS Land Cover information: this will allow not to mix together grassland,savannas and forests in Africa for example. The results are really striking in Australia, where the relationships strongly differs between different land cover types.

Also, we realized that the reliability of the hypothesis which claims that FRP could be used as a proxy of fire intensity depends on the land cover: FRP integrates all the radiative energy from the fire, from the flame front or from smouldering. Only the flame front is related to the rate of spread. In grassland, the flame-front will be the main contribution to FRP, but this is not always the case for other land cover. Therefore, separating our analysis depending on land cover also allows us to discriminate areas where FRP is a reliable proxy of fire intensity.

Please find our point-by-point answers to specific comments in the following.

1) Line 23 plant biomass distribution.

Answer: The text has been changed.

2) Line 25 rather ecological driver than climatic variable.

Answer: Through its effects on the carbon cycle, fire is an important climatic process. But this is true that fire is important for both ecological and climatic effects (as described later in the introduction). Since in this first paragraph we focus on climate modeling, we prefer to keep the sentence as it is.

3) Line 29 reliable burned area, active fires and fire intensity global dataset.

Answer: The text has been changed.

4) Line 45 fire patches vs raw burn area. Please could you explain?

Answer: Burned area integrates all fire patch areas into a single value. Recent studies now split analysis of the total burned area into patch level analysis allowing for a more precise information on ignitions and fire spread processes underlying the final burned area.

5) Line 54 please define BA here (burned area).

Answer: Actually we first used the term Burned Area on l. 30. We now introduce the term BA there.

6) Line 62 please detail MCD14ML. Best to give the complete name of the remotely sensed products you used and their DOI if available.

Answer: I will detail the dataset, and try to find the DOI.

7) Line 76 fire patch size why not fire patch area ?

Answer: We tried to keep the same terminology as in Laurent et al. 2018.

8) Line 74 “validated against Landsat fire polygons”.

Answer: The text has been changed.

9) Line 77 Standard Deviation Ellipse (SDE) Please could you explain how this parameter calculated? It does not seem further used in the manuscript except lines 87 and 89. One SDE covers approximately 68 percents of the fire patch. You applied a cutoff at SDE + 1 km, why not 2 SDE?

Answer: The SDE were obtained with the “aspace“ R package. We have modified the text (l. 80). Taking 2 SDE as the matching radius with FRP pixel would have yield lots of double association in the database. We prefer to be conservative, even if this result in a reduction of the usable number of fire patches.

10) Line 90 30-day buffer seems very long. During this delay surface reflectance may drastically change with resprouter shrubs or some bunchgrasses.

Answer: We agree, but this corresponds to the high uncertainty on the burn scar detection from BA dataset. Moreover, we did some test by reducing the 30 day buffer, and this had no significant effect on the result (it only reduces the number of patch with associated FRP).

11) Line 95 you wrote "In this analysis, we used FRP as a proxy of fire in tensity, later called FI". Further we still found FRP in the text and in the graphs.

Answer: Following the remarks of the other referees, we prefered to change FI into FRP throughout the text.

12) Line 112 "Brazilian tropical savannas". On fig 1b, most red dots are located across Argentina and not across Brazilian tropical savannas!

Answer: Yes, we agree. We have changed "Brazilian tropical savannas" to "Patagonia".

13) Line 125 please define the meaning of GFED. Please use the full names of the regions in Table 1.

Answer: We have inserted the full name on line 120, the first time GFED is mentioned.

14) Line 126 fitted rather than interpolated.

Answer: We have changed the text.

15) Line 130 humped relationships in CEAM, EQUAS, SEAS. This type of "humped" relationships seems to occur elsewhere? You presented these three areas as equatorial biomes. This means closed to equator or with a particular climate pattern? (See my previous comment on your geographical cutting).

Answer: We now separate each GFED region depending on their vegetation types, using land cover from MODIS. This has yield a new paragraph in the Methodology and the Results section.

16) Line 139 MW-1

Answer: Text has been changed.

17) Line 206 percolation or cellular automata?

Answer: We meant percolation.

18) Figure 2 FI in the figure legend and FRP in the x-axis. Y-axis scales drastically change depending of geographic area and so complicate the reading.

Answer: This was a mistake, we have modified the text.

19) Figure 3 are you sure that this figure is necessary (see Table 1 content).

Answer: We agree, especially now that we are separating GFED regions in multiple biomes. We have removed the figure.

Answer to reviewer #3

Major concerns:

I) The manuscript lacks a proper discussion (and references) of potential issues that may arise when estimating fuel consumption and subsequently fire intensity from FRP. FRP observations from MODIS represent infrequent snapshots of energy release across the pixel area (at best ∼1km2 at nadir). This results in a number of difficulties when linking FRP to fire temperatures or -intensity- of which several will likely be a function of environmental gradients. First, FRP is an estimate of energy release across an entire pixel, ∼1 km2 at nadir for MODIS. It is very uncertain what fraction of the grid cell is actually burning (and this is likely a function of fuel loads and other aspect of fire behavior). Yet, this is a requirement to estimate fire intensity because if 1% of the pixel produces 10 MW of energy, or 50% of the pixel produces the same amount makes a difference of 50 times the "intensity". Second, several studies suggest that vegetation structure (in particular tree cover) also have a significant effect on the relationship between fuel consumption and observed FRP (e.g. Roberts et al., 2018 RSE). Third, the sensitivity of the MODIS instruments to detect active fires (i.e. minimum FRP that can be observed) is a direct function of the scan angle and is up to a factor of 5 lower at large scan angles compared to nadir. This may be important when looking at distributions (e.g. median), because you are likely to strongly underestimate the occurrence of low FRP values. Fourth, the fire diurnal cycle (a function of fuel conditions, vegetation type, and climate) also produces a sampling error, since there are only few daily overpasses and in some ecosystems fire activity may peak already early in the morning while in others this maybe later in the afternoon.
It would be important to properly discuss what “MODIS FRP” actually represents. I also disagree with the statement “This is in agreement with .. , since these quantities are two proxies of the number of ignitions.” (lines 120-122). I do not see how the number of active fire detections is related to ignitions? A single fire may produce up to hundreds of active fire (FRP) detections if it becomes large enough and burns for a long period of time. Several studies have linked active fire detections (with or without FRP) to total amounts of fuel consumption (or biomass burned), which would be a function of area burned, fuel loads and other conditions. Moreover, looking at the distribution of FRP detections may become problematic here. In high fuel load temperate and boreal forested systems a large share of the active fire detections may come from smouldering rather than the active fire front (and ratios may change over the fire’s lifetime), while for grasslands it may be mostly actively flaming fire fronts that are observed. In this light it would be important to much better define “fire intensity” (i.e. what do the authors want to measure exactly?), and discuss how using FRP as a proxy for this quantity may be further influenced by the above mentioned limitations.

Answer: We highly agree with the numerous comments on the use of FRP stated by the reviewer. First, using FRP as a proxy of Fire reaction intensity is not straightforward, and we agree that it should depend on the considered land cover. We decided to replace all occurrences of ‘Fire Intensity’ in the text with ‘Fire Radiative Power’ (including the title), since this is what we are really observing in the analysis. Then, we discuss our result under the hypothesis that FRP could be used as a proxy of fire reaction intensity (that we now clearly define in the text), and we discuss the limitation of such an approach. Note that we are now dividing each GFED regions into different land covers (forests/savannas/grasslands, see minor comment 9)). This separation is really helpful, because we can now separate in each GFEd regions grasslands (where FRP can be safely used as a proxy of fire intensity) from forests (where canopy could intercept part of the emitted radiation, and where smouldering could significantly contribute to the detected FRP). We added references to support the discussion.

We have also added in the discussion a paragraph (and references) about the spatial and temporal errors of MODIS instruments. We also think that keeping the separation into GFED

regions allows to mitigate the sampling error : for example, if detection threshold varies with latitude, we can expect it to significantly differ between BONA and NHAF, but to vary less within each region. We then expect FRPs to be equally related to FI within a biome, whatever the FRP intensity, so the relationships with FS is conserved in our results. This uncertainty in FRP was also pointed out by reviewer 1 for which we also provide additional information and references on detection thresholds. In the following, we displays a draft of the paragraphs we would like to add to the discussion section:

"In the previous section, we hypothesised that FRP could be used as a proxy of fire reaction intensity. We now focus on the limitations of such an approach. First, the energy released by a wildfire can be decomposed in three parts : convection, conduction, and radiation. FRP only represents the radiative part of the energy emitted by a fire. Moreover, the fire reaction intensity used in Rothermel's equation does not share the same spatial extent as FRP : fire reaction intensity pertains to the flaming front of the fire, while FRP integrates all the radiative energy emitted over a 1 km^2 window. This means that radiation emitted from smouldering can also contribute to FRP, not only the flaming front. The impact should differ for different vegetation types : smouldering fires are more frequent in forested areas, whereas in grasslands most of the detected radiative power will be released by the active fire front. Another issue appears from the integration of radiative energy over the 1 km^2 window : it is impossible to know if the detected FRP arises only from a fire covering the full 1 km^2 area or only from a smaller fraction of the FRP pixel. However, we can expect this effect to be mitigated by the fact that our analysis does not account for very small fires, since the FRY database does not provide fire patches smaller than 107 ha for MCD64A1. Finally, a recent study (Roberts et al. 2018) used 3D radiative transfer simulations to show that the canopy structure intercepts part of the FRP emitted by surface fires. This means that the FRP measured from remote sensing for forested areas and savannas could underestimate the real FRP. We can also expect this underestimation to vary with tree species. For example, it is probable that the amount of radiation energy intercepted by the canopy differs strongly between canopy fires from highly flammable black pines from BONA (Rogers et al. 2015) and surface fires from pine needle bed in BOAS. All these considerations emphasize the importance to split the study of the relationship between fire size and FRP in different vegetation types, since the reliability of using FRP as a proxy of fire reaction intensity depends on it."

"The amount of radiative energy reaching the MODIS instruments is much smaller at large scan angles than at Nadir. This means that the MODIS instruments will be less sensitive to low values of FRP at high latitude (Giglio et al. 2003, Schröder et al. 2005). This could explain the difference of the distribution of FRP associated with fire patches in BONA (Figure 2) : the stronger asymmetry of the distribution in this region (i.e. the larger tail toward high FRP values) could arise from missing active fire data from less intense fires in this region. The temporal sampling of FRP also differs with the latitudinal coordinate : the number of satellite overpass is larger at high latitude than at the equator (from 2 observations per day until 15 at the poles, Giglio et al. 2006). This should rise the probability to recover FRP information for fire patches at high latitude, assuming that their radiative intensity is high enough to exceed the higher detection threshold at larger scan angles. Also, in some regions (such as NHAF and SHAF) fires exhibit a strong diurnal cycle (Giglio et al. 2006). The detection rate of active fires will therefore be higher if the peak of diurnal intensity is synchronized with satellite overpass. However, we can expect the sampling error rate and the variation of FRP sensitivity with latitude to be more homogeneous within each GFED regions that at global scale."

Please find our point-by-point answers to specific comments in the following.

1) Line 87. That is ok, but what do you do if you have two adjacent fire patches? Are you double counting the active fire detections?

Answer: Yes, this is what we do. However, note that we are performing the matching using Standard Deviation Ellipses (SDEs) from the fire patches, since these are the information provided by the FRY database. SDEs delimit 2/3 of the burn pixel of the fire patches, and are localized around the central area of the patch. This should limit the amount of attributing twice a active fire pixel.

2) Line 95. "‥, we compute for each patch the mean FRP value of all .. ". This isn't entirely clear to me, do you first estimate the mean of each patch and then look at the median across patches? Again, it would be important to understand what the distributions look like (e.g. across land cover types) to understand the potential implications of such decisions.

Answer: Yes, this is what we do. We have added as supplementary plots :

- a map of the ratio of missed matches between fire patches and active fire pixel data.

- a histogram showing the global fire size distribution of fire patches and the distribution of fire patches without recovered active fire information.

We now discussed these plots in the discussion, they help us to discuss the limitation of using FRP as a proxy of Fire Intensity.

3) Line 155 "In each 1x1 cells", typo.

Answer: The mistake has been corrected.

4) Lines 155 – 160, please move this to the methods section, accompanied by a short explanation on how that helps to answer your research questions.

Answer: We have moved the section to the methodology section.

5) Line 170 "Following the hypothesis from Rothermel's equation", maybe be a bit more specific here and add references. For clarity you could also repeat your own objectives here, e.g. "We aim to investigate if fire size and intensity are driven by a same set of environmental and climate conditions.." Also, I am somewhat surprised that in addition to speed, the authors don't mention fire duration as a potential driver of larger fire sizes.

Answer: We agree. This is also related to the first concern of reviewer 2. We are now giving more details about Rothermel's equation.

6) Line 174 "Tropical areas" is not a vegetation type, delete?

Answer: We meant tropical forest. We now separate each GFED regions in biomes.

7) Line 178 "experience limited fire energy" what does this mean? Do you mean to say something like "In equatorial areas with high annual rainfall, biomass burning is characterized by low spread rates are combustion completeness (cite), resulting in a more gradual release of energy from fires"?

Answer: Yes, this is what we meant. Also, if the fuel is not totally dry, part of energy release by the fire will be 'wasted' to vaporize the remaining water in the fuel.

9) Lines 198 – 214, this is an interesting discussion. However, what I miss here is a discussion on the potential influence of the spatiotemporal progression of the fire season. For example, the authors clearly find highest median FRP in more arid environments (e.g. southern Africa or interior Australia), these regions also tend to burn later in the fire season. So in Figure 2 when focusing e.g. on Australia. The increase in "fire size : median FRP" ratio isn't that simply because we are first looking at a dominant signal from tropical northern Australia and then the signal becomes more and more dominated by interior Australia towards the end of the fire season? In that light I like the suggestion of reviewer #1 to take an approach that has a stronger focus on vegetation types, or areas that are otherwise more similar in terms of climate and vegetation compared to the GFED regions.

Answer: We agree. We are now separating each GFED regions in biomes. Note also that the separation into biomes is extremely helpful when it comes to the discussion related to your major concern for our analysis.

We put here the main answer to reviewer #1 about separating GFED regions in different land cover.

"We agree that relying only on GFED regions tends to mix together biomes with different biomass, fuel types, and with very different drought conditions. The problem with the use of drought datasets is that it is difficult to choose how to perform the separation between different levels of 'drought severity' : we could focus on the length of the drought season, or the severity of the Fire Danger Index, a combination of both, etc .... This choice would seem quite arbitrary, and would require a dedicated analysis. Instead, we propose to use MODIS Land Cover Data to separate each GFED regions in different biomes (Forested, Savannas, Grasslands/Shrublands, see Figure attached to the answer). We clearly see that the relationship varies with the biomes : the results are especially striking in Australia, where we see that the FRP/FS relationship differs a lot depending on the considered biome. Finally, since we do not directly study the relationship with biomass and drought, we removed from the abstract and the discussion the sentences where we claimed that the fire intensity is driven by these quantities."

10) Line 238 "Fire danger index has been constantly increasing during the last 50 years", I believe conclusions of that paper were a little more nuanced.

Answer: Actually, the article focused on the length of the fire season rather FDI. The author claims that the global fire season length has increase, even though fire season length can still decrease in some areas of the world. We have modified the text.

11) Figure 2: why do y-axis on the right side have no caption? Also, it's probably good to mention that "The background histograms represent the number of fire patches" in the caption. Finally, what is the size and ranges of the FRP-bins? Are you excluding bins with less than x fire patches?

Answer: We have added a caption on the y-axis, which represent the number of fire patches in each FRP bin (corresponding to the background histograms). We also modified the caption and give the ranges of FRP bins in the caption and in the text.

12) Table 1: "FI at maximum size (MW)", seems to be incorrect since you did not look at the FI for the largest fires. Something like "FI with largest associated fire patch sizes", or similar may be more appropriate.

Answer: Yes, we agree. We have modified the legend and the table. We have also found some similar occurrences in the text, and we have changed them.

Answer to short comment #1

Please find our point-by-point answers to specific comments in the following.

1) L35. Why is Van Wagner cited in relation to Rothermel's model, with which he had no relation whatsoever? Van Wagner was Canadian, and so involved with the Canadian fire behaviour prediction system, not the U.S.

Answer: This was a mistake. We removed the reference to Van Wagner.

2) L36-37. "whose rate of spread scales with a power function of the wind velocity, landscape slope and fire intensity." The authors are referring to reaction intensity, not fire intensity (aka fireline intensity, which is the product of rate of spread, fuel consumption and heat of combustion and can be correlated to a certain extent with FRP).

Answer: Yes. This was also a remark from all reviewers. We did not define clearly what we meant by fire intensity. We now explicitly say in the text that this is fire reaction intensity of the flaming front.

3) L41-42. "On the other hand, the velocity of fire propagation determines the amount of fuel entering the combustion zone, and therefore feeds back on the intensity of the fire event." Not sure what this means. Rate of spread is an intrinsic component of fire intensity but not because it affects fuel consumption.

Answer: We meant that a fire need 'new' fuel to continue to burn. There is therefore a feedback between fire intensity and rate of spread: an intense fire is more likely to propagate faster, therefore to have more fresh fuel entering the combustion zone, therefore to continue burning, etc ...

4) L42-43. "fire intensity also significantly impacts the fuel combustion completeness". It's the other way around, fuel consumption is an element in the calculation of fire intensity.

Answer: You are right. This was a mistake, and we removed the sentence from the text.

5) L57. This is general, i.e. not specific of Rothermel 0 s model. For given fuel conditions/ fuel types faster fires are more intense, and faster fires will become large.

Answer: Yes this is true. We have changed the text.

6) L95. Has fire intensity been defined?

Answer: See answer to comment 2.

7) L170. The hypothesis does not stem from Rothermel's model, it just happens that fire intensity by definition (Byram 1959) is the product of rate of spread, fuel consumption and heat of combustion, as mentioned before.

Answer: Yes, this is true that this effect rather depends from Byram definition of fire intensity, not from Rothermel's model. We will modify the text (and also mention that we used the Byram definition of fire intensity).

8) L221. "They can therefore propagate further than ground fire and fire resistant species

found in savannas and woodlands". This sentence is confusing. Fire in savanna is driven by grass, not by trees (which are resistant only in the sense that they are fire adapted).

Answer: We realized that this sentence was not clear. We rephrased it in the manuscript: ‘They can therefore propagate further than ground fire and fire resistant species found in savannas and woodlands in semi-arid tropical regions’
=> ‘they can therefore propagate further than herbaceous fires hardly turning into crown fires in savannas and woodlands in semi arid tropical regions.’

9) I think the interpretation of the findings, by being concentrated on the effect of fuel connectivity, is restrictive. The authors could improve the discussion by considering that the most powerful driver of fire spread/size is wind speed (see the switches of Bradstock 2010). Thus, fuels can be totally available to burn due to drought, and produce intense fires that are not that large because they do not coincide with strong winds and low relative atmospheric humidities. Thus, the annual cycle of fire extent and intensity is also a matter of timing of coincidence between drought and atmospheric conditions.

Answer: We agree, but this would require a dedicated analysis using wind power/wind orientation datasets. We will mention this in the discussion.

Varying relationships between fire ~~intensity~~radiative power and fire size at global scale

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Abstract. Vegetation fires are an important process in the Earth system. Fire intensity locally impacts fuel consumption, damage to the vegetation, chemical composition of fire emissions but also how fires spread across landscapes. It has been observed that fire occurrence, defined as the frequency of active fires detected by the MODIS sensor, is related to intensity with a hump-shaped empirical relation meaning that occurrence reaches a maximum at intermediate fire intensity. Raw burned area products obtained from remote-sensing can not discriminate between ignition and propagation processes. ~~Here we use the newly delivered global FRY database, which provides fire patch functional traits including fire patch size from satellite observation, t~~To go beyond burned area~~,~~ and to test if fire size is driven by fire intensity at global scale as expected from empirical fire spread models, we used the newly delivered global FRY database which provides fire patch functional traits based on satellite observation, including fire patch size, and the fire radiative power measures from the MCD14ML dataset. This paper describes the varying relationships between fire size and fire radiative power across biomes at global scale. We show that in most fire regions of the world defined by the the GFED database, the linear relationship between fire ~~intensity~~radiative power and fire patch size saturates for a threshold of intermediate intensity fires. The value of th~~is~~e threshold differs from one region to another, and depends on vegetation type~~, and we suggest that it might be driven by drought, and the amount of available biomass~~. In the most fire-prone savanna~~some~~ regions, once this threshold is reached, ~~we also observe that~~ fire size decreases for the most intense fires, which mostly happen in the late fire season. According to the percolation theory, we suggest that th~~is~~e decreasing of fire size~~effect~~ for more intense late season fires is a consequence of the increasing fragmentation of fuel continuity along the fire season ~~so~~ and suggest that landscape-scale feedbacks should be developed in global fire modules.

1 Introduction

Fire is a major perturbation of the Earth system, which impacts the plant biomass distribution and vegetation structure, the carbon cycle, global atmospheric chemistry, air quality and climate (Bowman et al. 2009). Fire is therefore recognized as an essential climatic variable (GCOS 2011), and the potential impact of global warming on drought severity and fire season length is a key scientific questio~~n important research topic~~ (Flannigan et al. 2009, Krawchuk et al. 2009, Aragão et al. 2018) to understand its role within the Earth system. ~~As a result, m~~Most Dynamic Global Vegetation Models (DGVMs) have included fire modules (see Hantson et al. 2016, Rabin et al. 2017 for a review) to ~~provide reliable~~improve the prediction of the impact of fire on ~~of~~ vegetation dynamics and the carbon cycle. Substantial efforts have been devoted in the past decades to create reliable ~~global~~ burned area (BA), active fires and fire ~~intensity~~radiative power (FRP) global datasets which allow to quantify the fire perturbation since the beginning of the 2000's (Mouillot et al. 2014) and ~~for~~ benchmark~~ing of~~ DGVM~~s~~ fire modules.

A fire can be decomposed as a two-step process, the ignition and the propagation (Pyne 1996, Scott et al. 2014). Potential fire ignitions are set by lightning strikes and humans (deliberately or accidentally), and the probability that an ignition turns into a spreading fire event mainly depends on fuel type and its moisture content at the location of the ignition. The Rothermel's equation (~~Wagner 1969,~~ Rothermel 1972) has long been used to model fire propagation in landscape fire succession models (Cary et al. 2006), whose rate of spread scales with a power function of the wind velocity, landscape slope and fire intensity. However, this model, used by ~~in most DGVM~~ processed-based fire modules in most DGVM, has only been benchmarked on experimental and localized fires, discarding topographic and landscape effects. ~~However~~Besides, for larger natural fires, the continuity of the fuel bed also has an impact on fire propagation: a homogeneous fuel bed usually promotes fire propagation (Baker et al. 1994) while fragmented landscape with a heterogeneity of fuel patches reduces fire spread (Turner et al. 1989). On the other hand, the velocity of fire propagation determines the amount of fuel entering the combustion zone, and therefore feeds back on the intensity of the fire event. In addition to its coupling with fire propagation, fire intensity also significantly impacts ~~the fuel combustion completeness (Crutzen et al. 1979),~~ the chemical composition of the emissions (Tang et al. 2017), the amplitude and severity of vegetation damage and its post-fire regeneration ability (Bond and Keeley et al. 2005). As a result, analyses focusing on fire patch properties, such as fire patch size and shape,~~es~~ rather than on ~~raw~~simple ~~burn area~~ BA have emerged in the last decade. Information on ~~in order to study~~ the fire patch size distribution (Archibald et al. 2010, Hantson et al. 2015, Laurent et al. 2018) ~~or as a tool~~ can be used to map the different fire regimes at global scale (Archibald et al. 2013), and edge effects could reveal landscape scale processes leading to the observed shapes of burned patches (Greene et al. 2005, Cary et al. 2009).

Recent studies (Pausas and Ribeiro et al. 2013, Luo et al. 2017) have shown that fire occurrence, defined as the number of remotely detected active fires in unit of time per unit area, increases with fire intensity up until a threshold is reached (so-called Intermediate Fire Occurrence-Intensity (IFOI) hypothesis) above which occurrence decreases with increasing intensity. Since ignition and propagation are different processes and are not driven by the same climatic variables, it is necessary to go beyond fire occurrence and ~~burned area~~BA and to consider individual fire events. Here we document and investigate the relationship between fire patch size derived from BA data and ~~fire radiative power (~~FRP~~)~~ at global scale based on remote sensing information. FRP measures the energy emitted through radiative processes released during the combustion, and can be associated with fire intensity all along the fire burning process (Wooster et al. 2005, Ichoku et al. 2008, Barrett and Kasischke 2013, Wooster et al. 2013). A positive relationship between fire patch size and ~~fire~~the reaction intensity of the fire front is expected ~~from the Rothermel's equation~~ at least for small fire size, whose propagation rate has been benchmarked using laboratory experiments.~~,~~ B~~b~~ut we do not know if this holds up at global and regional scale ~~and~~ for bigger fires~~-~~, usually reaching longer temporal scales with varying wind directions and atmospheric circulation, and larger spatial extent.~~: where landscape fragmentation could act as a natural barrier against fire propagation, f~~ Fire patch size may not continue to increase with fire intensity above a certain size due to landscape fragmentation could act as a natural barrier against fire propagation. To uncover the fire size-intensity relationships, we assembled~~matched~~ the information on fire patch size recovered from the FRY global database (Laurent et al. 2018) based on the MODIS MCD64A1 and the MERIS FireCCI41 ~~sensors~~burned area products, with ~~fire radiative power (~~FRP~~)~~ using active fire pixel data from the MCD14ML dataset.

2 Data and Methodology

We used the FRY database containing the list of fire patches characterized by their morphological traits, including fire patch size, at global scale (Laurent et al. 2018). Fire patches were derived from the MERIS fire_cci v4.1 (later called FireCCI41, Chuvieco et al. 2016) and the MCD64A1 Collection 6 (Giglio et al. 2016) ~~burned area (~~BA~~)~~ pixel products. The FireCCI41 product provides the pixel burn dates for the period 2005-2011 and is derived from the ENVISAT-MERIS sensor, with a spatial resolution of 300x300m~~,~~ and a 3-day revisi~~s~~t frequency at the equator.~~;~~ The MCD64A1 product, derived from the MODIS sensors, provides pixel burn dates at global scale over the period 2000-2017 with a coarser resolution (~500x500m) but a more frequent revisit time (1 day at equator).~~;~~ The pixel burned dates are combined using a flood-fill algorithm (Archibald et al. 2009), which is parametrized by a cut-off value. This cut-off value corresponds to the maximum time difference between the burn date of neighbouring pixels belonging to the same fire patch. These global datasets have been thoroughly compared by the authors of the FRY database, locally compared using North America Forest Service fire patch database (Chuvieco et al. 2016) and validated against ~~l~~Landsat fire polygons in the Brazilian cerrado (Nogueira et al. 2017). ~~Fire patches in~~The FRY database ~~are~~ is organized in 8 datasets (2 surveys times 4 cut-off values), and provides for each individual fire patch~~,~~ a set of variables, called fire patch functional traits, ~~are provided such as~~including the geo-location of the patch centre, the fire patch size (later called FS, in hectares), and different indices on fire patch morphology. Standard Deviation Ellipses (SDE) are fitted by Laurent et al. over each fire patch larger than 5 pixels (using the “aspace” R package),~~)~~ and the geo-location of their centres, half-axes and orientation in longitudinal/latitudinal coordinate system are also ~~fitted~~provided for each patch~~es, and their half-axes and orientation are provided in longitudinal/latitudinal coordinate system.~~, as well as t~~T~~he values of the minimum, mean and maximum pixel burn dates.~~, and the mean burn date of the fire patch pixel are also provided~~.

Active fire pixel data from the MCD14ML dataset (Giglio et al. 2006) consists in a list of geographic coordinates of individual active fire pixels detected by the Terra and Aqua sensors onboard the MODIS satellite for the period 2000-2017 with a resolution of 1x1km. For each pixel, the dataset provides the date and hour of burn of the active fire pixel, along with its ~~fire radiative power (~~FRP~~,~~ (in MW). FRP represents the energy emitted by fire through radiative processes (i.e. the total fire intensity minus the energy dissipated through convection and conduction) over its total area. It is widely used as a proxy for fire impact assessment (Barrett and Kasischke 2013, Sparks et al. 2018), biomass combustion rates (Roberts et al. 2005) or fire event (Hernandez et al. 2015) and fire spread (Johnson et al. 2017) modelling. We performed a spatio-temporal matching between active fire pixel data and all the fire patches from the FRY database in order to recover the average FRP for each fire patch. To do so, we consider that an active fire pixel belongs to a fire patch if it fulfils the two following conditions:

- The centre of the active fire pixel must be located within the SDE of the fire patch. Since the side of an active fire pixel is 1km, we also consider that an active fire pixel located at a distance of 1km or less from the area covered by the SDE belong to the fire patch.
- The detection date of the active fire pixel must lie between the minimum minus a 30 days buffer and maximum burn date of the BA~~burned area~~ pixels of the fire patch. The 30 days extension is used to account for the possible time lag between the detection of an active fire pixel and its associated burned date pixels.

Once the active fire pixels belonging to each fire patch ~~have been~~were obtained, we compute for each patch the mean FRP value of all associated pixels~~. In this analysis, we use FRP as a proxy of fire intensity, later called FI (Wooster et al. 2005, 2013)~~. The spatio-temporal matching sometimes fails to recover any active fire pixels for some fire patches. Such fire patches (~20-25% of each sample) were discarded from the analysis. We observed that the number of fire patches without attributed active fire pixels raises as the cut-off decreases (see Supplementary Tab 1). This can be explained by the fact that, for low cut-off values, a real fire event can be split by the flood-fill algorithm in different smaller fire patches. Using a shorter value for the temporal buffer (10 days)~~,~~ slightly raises the failure rate of the matching, but had no significant impact on the results presented in this analysis.

In the following, we studied the relationship between FRP and FS in each region defined by the Global Fire Emission Database (GFED, Giglio et al. 2013, Supplementary 1). Since different vegetation types can occur within a GFED region (and consequently different amount of biomass or drought severity), we split all of them in three vegetation types using the GLCF MODIS Land Cover data (Channan et al. 2014) and explore the relationship between FRP and fire size for each vegetation type in each GFED regions. The vegetation types are defined by grouping together MODIS Land Cover categories: "forests" stands for all the forested land cover types (evergreen/deciduous needleleaf/broadleaf forests and mixed forests), "savannas" for savannas with woody savannas, and "grasslands/shrublands" stands for grasslands with open and closed shrublands. The spatial extent corresponding to these three vegetation types can be found in Supplementary Figure 2.

In each 1°x1° cell, we split the fire season into three periods: early, corresponding to the 4 months before the month with the highest BA, middle, corresponding to the peak BA month, and late fire season corresponding to the 4 months after the peak BA month. We did not split the fire patch distribution in different FRP categories, because of the big asymmetry of the number of fire patches between high and low intensity fires. For each period, following the same methodology as in Laurent et al. 2018, we fitted a power law against the fire patch size distribution to estimate the power-law slope parameters β_{begin}, β_{middle} and β_{end}. These β parameters allow to investigate the asymmetry of the fire size distribution in each cell. High β values implies that the size distribution is dominated by small fires.

The results presented below have been computed for each of the 8 different fire patch datasets of the FRY database. However, we will further only focus on the results obtained from the MCD64A1-derived fire patch dataset, with a cut-off value of 14 days. The figures obtained for the FireCCI41 fire patch product with a cut-off of 14 days (which span the years 2005 to 2011) can be found in Supplementary. The same analysis was also performed with a cut-off value of 3 days for both MCD64A1 and FireCCI41: testing another extreme cut-off value allows us to estimate the impact on the results of the temporal threshold parameter used to reconstruct fire patches by Laurent et al. (2018) on the results.

3 Results

The median FS and median FIFRP are displayed on Figure 1. Large and intense fire patches are located in Australia, in the grasslands of Kazakhstan, in Namibia and, in Sahel, in forested regions of North America and Western Siberia, and in the Brazilian tropical savannasand in Patagonia. These areas usually coincide with more intense fires. The Hhighest mean FIFRP values are also reached in South Australia, in the Mediterranean Basin and in the forested areas of Western USA and boreal North America. On the contrary, fires are both smaller and less intense in croplands of North America, Europe and South East Asia, and in African savannas. The fraction of BA in the cell each year is also displayed.

The relationships between the median, 25th and 75th quantiles of FS based on MCD64A1 with a cut-off value of 14 days, and FIFRP for different GFEDsub- regions defined by GFED (Giglio et al. 2013, Supplementary 1) for MCD64A1 with a cut-off value of 14 days are shown in Figure 2. The color of the dots and error bars represents the average mean of the minimum burn dates of the fire patches in each bin of FIFRP, and the background histograms the number of fire patches in each FIFRP bins. In all GFED regions, the number of fire patches peaks at low to intermediate FIFRP values (~20-30 MW). This is in agreement with the observations from Luo et al. (2017), who showed that fire occurrence peaked at intermediate (~30 MW) FI values. Such an agreement between fire occurrence from active fire data and the number individual of fire patches from BA is expected, since these quantities are two proxies of the number of ignitions.

~~Our study not only documents the effect of FI on the number of ignition, but also on fire patch size.~~ In most of GFED regions, we note that median FS and quantiles decreases once a ~~FI~~FRP threshold is reached (Figure 2). In order to smooth the estimation of this ~~FI~~FRP threshold (later called ~~FI~~FRP$_{MAX}$) above which FS seems to saturate, we ~~interpolated~~fitted a four-degree polynomial function to the data and determined the ~~FI~~FRP at the maximum median FS value of the fit. The results are displayed in Table 1~~ and Figure 3~~. ~~For these regions, once FI gets above this regional threshold, the median and 75th quantile of FS decreases.~~

~~Equatorial biomes in~~ Northern Hemisphere Africa (NHAF), ~~Central America (CEAM),~~ Equatorial Asia (EQAS) and Southeast Asia (SEAS) experience a humped relationship between FS and ~~FI~~FRP. At low ~~FI~~FRP values (30 to 80 MW), the median and quantiles of FS increases with ~~FI~~FRP and reaches a maximum value at low to intermediate ~~FI~~FRP (Table 1, Figure 2~~3~~). We also identified in Figure 2 that the fire patches associated with intense fires having a ~~FI~~FRP above the regional threshold tend to occur later in the fire season. In Central America (CEAM)~~tropical areas of Northern Hemisphere Africa (NHAF)~~, Northern Hemisphere South America (NHSA), Southern Hemisphere Africa (SHAF), Southern Hemisphere South America (SHSA), and Australia (AUST), but also in Boreal Asia (BOAS), the relationship between the median and quantiles of FS vs ~~FI~~FRP is similar. However, the maximum FS is reached at higher ~~FI~~FRP values (from 75 to 125MW) than for ~~equatorial biomes~~NHAF, EQAS and SEAS, and the decrease following the maximum FS is more gradual. Intense fire events also appear later in the fire season for BOAS and AUST, and AUST exhibits ~~the peculiar aspect reaching~~ the highest FS/~~FI~~FRP slope (9.0 ha.MW^{-1} compared to 0.6 to 4.4 ha.MW^{-1} for other regions). By contrast, in Boreal North America (BONA), Temporal North America (TENA) and Europe (EURO), and Central Asia (CEAS), mean FS constantly increases with ~~FI~~FRP and only reaches a plateau at very high ~~FI~~FRP (~196 MW for BONA, ~215 MW for TENA, ~~and~~ ~240 MW for EURO and 277 MW for CEAS). In those temperate and boreal regions, we did~~o~~ not observe the humped shape relation with a decrease of FS for high ~~FI~~FRP that occurs in other GFED ~~sub-~~regions (Figure 2). Middle East (MIDE) also displays a positive correlation between median FS and ~~FI~~FRP, but the statistics for intense fire events is too low to infer any significant relationship at high ~~FI~~FRP values.

Figure 3 displays the same analysis as figure 2, but each GFED region is subdivided into 3 vegetation types (as defined in the Methodology section), allowing an overview of the contribution of each vegetation type by region. For BONA, TENA and EURO, mostly dominated by forest fires, we observe that the generic pattern obtained in Figure 2 is similar to the one observed for the 'forests' vegetation type, while the other vegetation types display a more humped-shape relationship. In tropical areas (NHSA, SHSA, NHAF, SHAF, AUST), the generic pattern observed in Figure 2 is similar to the one observed for the "savannas" and "grassland/shrublands" vegetation types, highlighting the uniform pattern in these two dominant vegetation types within the region, only differentiated by a higher median fire size for "savannas". 'Forests' vegetation types display a more linear relationship, closer to the one observed in temperate and boreal areas. In conclusion, the behavior of the relationship between FRP and FS obtained for each GFED region is actually representative of the main dominant vegetation types composing these regions, while the non-dominant vegetation types may experience another pattern. In all regions, savannas and grasslands ecosystems experience higher median fire sizes with a humped shape FS/FRP relationship, while forested areas experience a more linear relationship.

Figure 4 shows ~~in~~for 1°x1° cells at global scale the month with the largest median FS, the month with the highest median ~~FI~~FRP, and the phase shift between these two months. For most African cells, the month with highest median ~~FI~~FRP is shifted between 3 to 6 months after the month with highest FS. These cells correspond to the regions where high burn area (Figure 1, Giglio et al. 2013) and a high density of fire patches are detected (Laurent et al. 2018). A narrower shift is observed in SEAS, northern AUST, and in the cells of South America with a slightly lower number of fire patches and lower

BA. In Northern America (BONA and TENA), BOAS, and central and south AUST, no shift is observed, which means that the largest fires and the most intense fires happened concomitantly during the fire season. Some cells (mainly in Sahel and eastern BOAS/CEAS) displayed a negative shift, meaning that the most intense fires happened sooner than the largest fires.

~~In each 1°x1° cells, we split the fire season into three periods: early, corresponding to the 4 months before the month with the highest BA, middle, corresponding to the peak BA month, and late fire season corresponding to the 4 months after the peak BA month. We did not split the fire patch distribution in different FI categories, because of the big asymmetry of the number of fire patches between high and low intensity fires. For each period, following the same methodology as in Laurent et al. 2018, we fitted a power law against the fire patch size distribution to estimate the power-law slope parameters β_{begin}, β_{middle} and β_{end}, and~~ The global maps of power-law slope parameters β_{begin}, β_{middle} and β_{end} (respectively for the beginning, middle and end of the fire season) are displayed ~~the resulting maps~~ on Figure 5. The β parameters ~~were~~are only computed when more than 10 fire patches are available during the considered period, to ensure a sufficient number of patches in the fit. The differences between β_{end} and β_{begin} are also shown in Figure 5. The h~~H~~ighest β values (either β_{begin}, β_{middle} and β_{end}) ~~happened~~ were mainly obtained in NHAF, northern SHAF, NHSA, SHSA and SEAS, as observed in previous fire size distribution analysis (Hantson et al. 2015, Laurent et al. 2018). In these regions, we found that the value of β is higher at the end of the fire season than at the beginning, meaning that the proportion of small fires rises through the fire season, supporting our early results that late fire season don't get larger with increasing FRP. In AUST, the β value remains constant all along the fire season, and ~~it~~ increases in eastern BONA, TENA~~AS~~, and eastern BOAS, suggesting that later season fires are more dominated by larger fires. For other regions, the limited number of fire patches render difficult the interpretation of the evolution of β through the fire season.

4. Discussion

Following the hypothesis from Rothermel's equation of fire spread, and considering that FRP can be used as a proxy of fire reaction intensity (Wooster et al. 2003, 2005), we used the ~~newly delivered~~ global fire patch database FRY to test if high FRP~~FI~~ fires propagate faster and are therefore systematically larger than low FRP~~FI~~ fires. We ~~conclude~~found that this hypothesis is ~~only~~actually verified for low to intermediate ~~FI~~FRP in most ~~of~~ fire regions and for the three defined vegetation types~~, where FI and mean FS are positively correlated~~. ~~W~~We identified biome-specific ~~FI~~FRP vs FS relationships, with ~~FI~~FRP leading to maximum FS being higher in temperate/boreal forests, followed by grasslands, savannas ~~and grasslands,~~ and tropical ~~areas~~forests. ~~Following the varying constraint hypothesis (Krawchuk and Moritz 2011), stating that fuel biomass availability is the main driver of fire hazard at global scale, and that fuel moisture locally modifies this fire hazard when fuel is sufficient to propagate fires, we might expect higher fire spread and energy as a function of biomass, negatively controlled by fuel moisture. Equatorial areas, with continuous high rainfall amount, then experience limited fire energy due to low fuel dryness. Along this biomass gradient, temperate and boreal forests experience a slightly longer drought period during the fire season, inducing a theoretical higher fire severity. Beside these two biomes, grasslands (temperate or tropical) carry less biomass, yet still sufficient for spreading fires, and should experience the highest fire spread rate. We noted in the savanna biomes the peculiar case of AUST, with the highest values of the FRP/FS slope, twice higher than in other continents, but in accordance with local studies (Oliveira et al. 2015b). We suggest here the impact of wind speed being much higher in AUST compared to other continents (Lasslop et al. 2015).~~

I~~However, i~~n most fire-prone biomes, the positive relationship between FS and ~~FI~~FRP does not hold for larger and more intense fire patches (Figure 2), generally occurring later in the fire season, as previously observed in Australia ~~by~~ (Oliveira et al. ~~(~~2015~~a~~). This effect could be explained as follows: at the beginning of the fire season, when the fuel moisture content~~ of the fuel~~ is still high, FRP is limited as energy is consumed ~~for~~by fuel moisture vaporization (Alexander 1982, Pyne et al. 1996) and consequently, rate of spread and fire size also get~~s~~ limited~~ too~~. As the fuel becomes dryer along the fire season (Sow et al. 2013, Sedano and Randerson 2014, N'Dri et al. 2018) fires become more intense and potentially propagate further. However~~, as mentioned in the introduction~~, the propagation of larger fires can hit some limits due to~~because of~~ the fragmentation of the fuel matrix, ~~due to~~from intrinsic anthropogenic fragmentation, roads or grazing fields. The barriers~~, which~~ limit FS as fires became larger ~~through~~along the fire season: these large fires will have a high propensity to reach these barriers. As a result, in fire regions with fragmented vegetation~~,~~ such as African savannas, ~~SEAS~~Soth East Asia or at the interface between the amazon forest and croplands of South America, a maximum mean FS is reached at intermediate ~~FI~~FRP (Figure 2). The ~~FI~~FRP threshold differs however between these regions, possibly because their level of landscape fragmentation is different (Taubert et al. 2018).

If fire size would only be limited by the intrinsic structure of vegetation, we would not expect to see the decrease of the proportion of large fires toward the end of the fire season in fire-prone ecosystem ~~shown in~~ (Figure 5). If the number of individual fire events ~~was~~ is already high at the beginning of the fire season, the landscape becomes even more and more fragmented by BA~~burned area~~ scars (Oliveira et al. 2015) and fuel load decrease (N'Dri et al. 2018), meaning that the limitation of fire size due to landscape fragmentation will be higher for fires ignited later in the fire season (Teske et al. 2012). As a consequence, this mechanism may explain why the correlation between ~~FI~~FRP and FS becomes negative in Figure 2 during the late fire season in NHAF, NHSA, CEAM, EQAS and SEAS, and why β_{end} is higher than β_{begin}. This limitation of fire size for intense fires in those regions, possibly due to the feedback between fire and fuel connectivity at landscape level, is in line with the results obtained from Mondal and Sukumar (2016) relating the effects of recent past fires on fire hazard in dry tropical forests, and otherwise theoretically approached from the percolation model applied to wildfires by Archibald et al. (2012). This model shows that the amount of BA is maximized when both the fire spread probability and the fuel matrix connectivity are high. BA dramatically drops if fire spread probability is too low (such as in the beginning of the fire season) or if the fuel array connectivity becomes too ~~low~~small (such as in the end of the fire season). Particularly, the percolation model shows that BA can drop~~ped~~ dramatically once 50-60% of the available fuel has burned, which is close to the maximum percentage of BA detected by both MCD64A1 and FireCCI41 products (Giglio et al. 2013, Chuvieco et al. 2016). The IFOI hypothesis, proposed by Luo et al. (2017) to explain why fire occurrence is limited by fire intensity, can be interpreted as a direct consequence of percolation theory applied to fire-prone ecosystems.

For regions where fire events are less frequent, such as in BONA, TENA and EURO (Figure 2), there is no significant limitation of fire spread and fire size, suggesting that the fragmentation of landscape either from land use or from early season burn scars does not limit fire spread (Owen et al. 2012). Fire size remains positively correlated with fire intensity all along the fire season. Moreover, the 75th quantiles for BONA and TENA is higher than for tropical regions (except AUST), most probably because tree species in BONA and TENA (e.g. spruce) are more flammable ~~(e.g. spruce), and~~ because crown fires are more frequent, and because these ecosystems experience an actual drought period compared to the tropics where rainfalls occur ~~all year long~~more frequently. They can therefore propagate further than herbaceous~~ground~~ fires hardly turning into crown fires in savannas and woodlands in semi arid tropical regions~~and fire resistant species found in savannas and woodlands in semi-arid tropical regions~~. In BOAS the relationship between FS and ~~FI~~FRP is different from the one observed in BONA and TENA. This could be a result from the less flammable vegetation and the highest number of ground fires in BOAS (Kasischke and Bruhwiler 2003). Moreover, BA detection of surface fires (and consequently, fire patch characterization) is known to be difficult in boreal Asia, and numerous discrepancies have been observed between the BA products obtained from different moderation resolution sensors (Chuvieco et al. 2016).

The median FS is globally lower for the datasets generated from FRY with smaller cut-off value (see Supplementary 1 and 2), because big fire patches tend to be split in smaller patches for lower cut-off values, reducing the average fire patch size. The median FS is also lower for the FireCCI41_derived datasets, due to its ability to detect smaller patches from its better spatial resolution. Changing the survey or the cut-off value does not impact the global distribution of large and small fire patches. Reducing the cut-off to 3 days does not change the observed relationship between FS and ~~FI~~FRP. The results obtained from the dataset derived from FireCCI41 follows the same trend, but for some GFED regions (TENA, EURO, NHSA, AUST), the seasonality is shifted one month later than for MCD64A1. Reducing the cut-off values lowers the temporal shift observed on Figure 4 at global scale (Supplementary 3 and 4), but the global distribution of the shift is conserved. Similarly, FireCCI41 yields smaller shifts than for MCD64A1, but with the same spatial distribution.

In the previous section, we hypothesised that FRP can be used as a proxy of fire reaction intensity but the limitations of such an approach should be mentioned. First, the energy released by a wildfire can be decomposed in three parts: convection, conduction, and radiation. FRP only represents the radiative part of the energy released by a fire. Moreover, the fire reaction intensity used in Rothermel's equation does not share the same spatial extent as FRP: fire reaction intensity pertains to the flaming front of the fire, while FRP integrates all the radiative energy emitted over a 1 km^2 window. This means that radiation emitted from smouldering can also contribute to FRP, not only the flaming front. The impact should differ for different wetness conditions and vegetation types: smouldering fires are more frequent in forested areas, whereas in grasslands most of the detected radiative power will be released by the active fire front. Another issue appears from the integration of radiative energy over the 1 km^2 window: very often active burning fire lines do not cover the whole 1-km^2 area so that measured FRP is a mixed signal from both active-burning and unburned areas. However, we can expect this effect to be mitigated by the fact that our analysis does not account for very small fires, since the FRY database does not provide fire patches smaller than 107 ha for MCD64A1. Finally, a recent study (Roberts et al. 2018) used 3D radiative transfer simulations to show that the canopy structure intercepts part of the FRP emitted by surface fires. This means that the FRP measured from remote sensing for forested areas and savannas could underestimate the actual FRP. We can also expect this underestimation to vary with tree species that are associated with different fire regimes. For example, it is probable that the amount of radiation energy intercepted by the canopy differs strongly between crown fires from highly flammable black spruce and jack pine forests from BONA (Rogers et al. 2015) and surface fires from larch-dominated forests in BOAS. These facts advocate the importance to differentiate the relationships between fire size and FRP in different vegetation types with different fire regime and fire adaptations, due to varying degrees of reliability of using FRP as a proxy of fire reaction intensity.

Thresholds of FRP detection vary between 9 and 11 MW (Roberts and Wooster 2008, Schroeder et al. 2010~~,~~) for the MODIS FRP products, below which reliable detection becomes impossible. In turn, analysis based on comparison with finer-resolution remote sensing products actually concluded that MODIS might underestimate by 20% the number of captured fire pixels, particularly for small fires (Wooster et al. 2012, Peterson et al. 2013). This 9-11 MW threshold falls in the first bin of the FRP histograms in Figure 2, and could therefore explain the peak of the number of fire patches at intermediate FRP (~20-30 MW). The amount of radiative energy reaching the MODIS instruments is much smaller at larger scan angles than at Nadir. This means that the MODIS instruments will be less sensitive to low values of FRP at high latitude (Giglio et al. 2003, Schröder et al. 2005). This could explain the difference of the distribution of FRP associated with fire patches in BONA: the stronger asymmetry of the distribution in this region (i.e. the larger tail toward high FRP values) could arise from missing active fire data from less intense fires in this region. The temporal sampling of FRP also differs with the latitudinal coordinate since the number of satellite overpasses is larger at high latitude than at the equator (from 2 observations per day until 15 at the poles, Giglio et al. 2006). This should raise the chance to recover FRP information for fire patches at high latitude, assuming that radiative intensity is high enough to exceed the higher detection threshold at larger scan angles. Also, in some regions (such as NHAF and SHAF), fires exhibit a strong diurnal cycle (Giglio et al. 2006). The detection rate of active fires will therefore be higher if the peak of diurnal intensity is synchronized with satellite overpass. However, we can expect the sampling error rate and the variation of FRP sensitivity with latitude to be more homogeneous within each GFED regions that at global scale.

Fire danger index has been constantly increasing during the last 50 years (Jolly 2015) and could impact fFire season length has changed over the last 50 years and is now longer in 25% regions of the worldand/or intensity all over the world (Jolly et al. 2015). An increase of drought intensity in fire prone environment could yield to more intense fire events, yielding larger BAburned area patches for each fire event. However, if the progressive fragmentation of landscape through the fire season limits fire size, then it can be expected that a longer fire season would only have a limited impact on the increase of BA in these regions. In the same way but on a longer time scale in less fire prone regions, previous large fires have been shown to limit FS in the recent timeframe in western US (Haine et al 2013), and previous landscape biomass composition, as a result of fire history, is a major factor affecting fire severity in boreal forests (Whitman et al. 2018). On the contrary, in regions where the quasi-linear relationship between fire size and FRP is valid even for high FRP, a longer fire season could dramatically increase burn area, particularly in North American forests and Europe (Gillett et al. 2004, Turetsky et al. 2011). This hypothesis does not account for the impact of increased severity of fire damage to the vegetation in these ecosystems, and its feedback on fire propagation and occurrence. Our results are consistent with those of Andela et al. 2017, who showed that, contrary to what would be expected from the rise of the fire danger index, BA tends to decline at global scale (25% loss between 1998 and 2015). This decline is especially strong in savannas and grasslands, because of agricultural expansion, which results in a reduction of burnable area and a more fragmented landscape (Kamusoko and ,Aniya 2007, Oliveira et al. 2017, Sulieman et al. 2018). Landscape fragmentation is also a tool used for fire management. Indigenous burning practices in West Africa promotes early burning and therefore landscape fragmentation in order to limit large and intense fire events which could occur at the end of the fire season (Laris 2002, Laris and Wardell 2006, Le Page et al. 2015, Archibald 2016). Similarly, US forest services used artificial fuel-breaks to fragment the landscape and limit fire size (Green 1977, Agee et al. 2000), as well as fire intensity (Ager et al. 2017).

Some DGVM fire modules explicitly simulate BA as the product of individual successful fire ignitions with mean fire size (Thonicke et al. 2010, Yue et al. 2014). In these models, fire size usually depends on wind speed, fuel bulk density and fuel load. Because of the reduction of the available fuel load due to burning by preceding fires, we can expect than BA saturates toward the end of the drought season in DGVMsIt is common than BA saturates toward the end of the drought season because of the reduction of the available fuel load due to burning by preceding fires, but this mechanism does not account for landscape fragmentation (due either to land use fragmentation or progressive fragmentation by fires). The LPJ-LMFire v1.0 (Pfeiffer et al. 2013), a modified version of the Spitfire module for pre-industrial global biomass burning, accounted for passive fire suppression due to landscape fragmentation. Further refining of process-based fire modules would require extensive comparison with fire patch data rather than raw BA.

5. Conclusion

We characterized for the first time the actual relationship between fire size and fire intensity using a combination of fire patch size and active fire datasets at global scale. We found that in most fire-prone ecosystems, fire size increases with fire intensity only at low fire intensity, reaches a threshold at intermediate intensity, and then starts to decrease. On the contrary, in temperate and boreal forests, FS and ~~FI~~FRP are proportional even for high fire intensity. This behavior is observed with significant differences between land cover types (shrublands/grasslands, savannas and forests) for both MCD64A1 and FireCCI41 products, and for all cut-off values used for fire patch reconstruction. We suggested that the FRP~~I~~ threshold value is ~~driven by drought severity, available biomass,~~influenced by the fragmentation of the landscape, and the feedback between fuel connectivity and burn area during the fire season. This fragmentation hypothesis is consistent with the percolation ~~model~~theory applied to fire spread. The fragmentation hypothesis should be further tested with higher resolution BA datasets, combined with fine temporal resolution land cover datasets characterizing the landscape fragmentation, associated with temporally varying fuel moisture data, and further considered in the development of fire-DGVM models. Additional information as fire shape complexity and elongation from the FRY database should bring substantial information to assert our conclusions.

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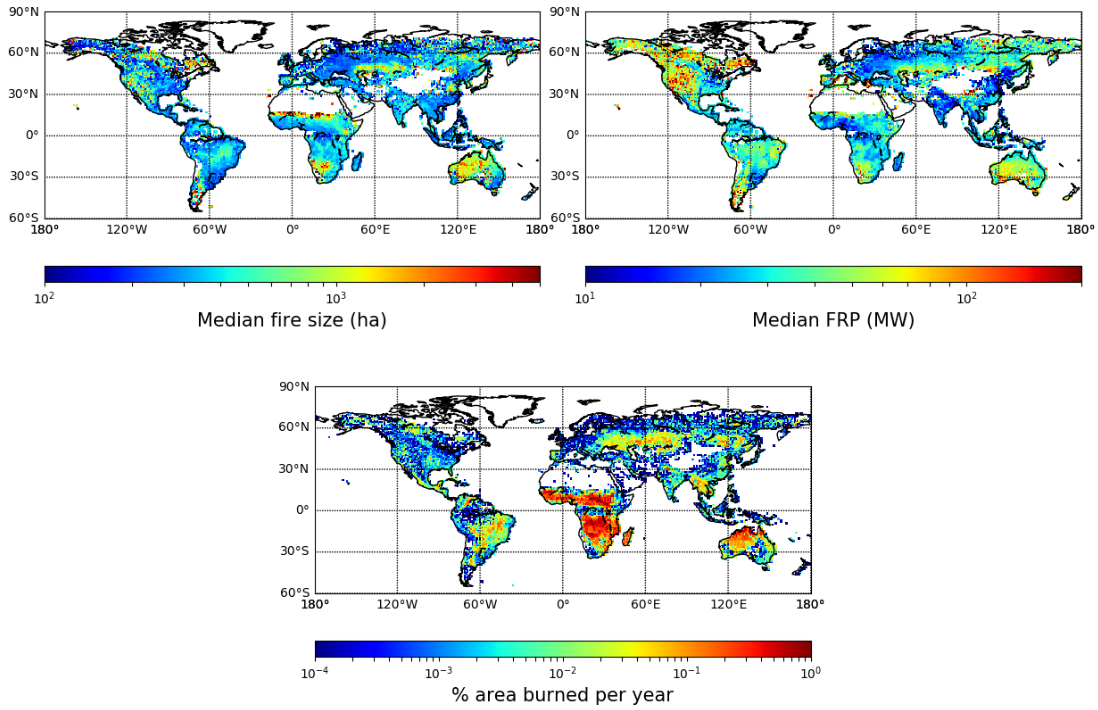
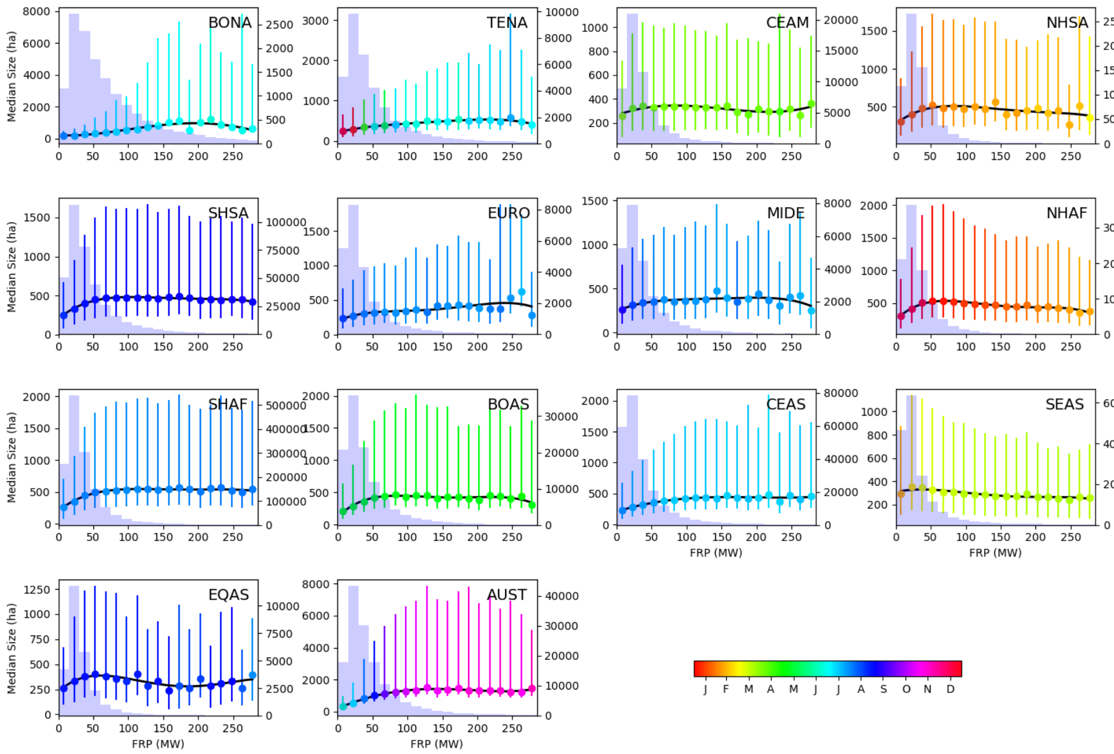


F~~i~~igure 1: Me~~d~~dian fire size ~~FS~~ (~~patch area~~ in ha), ~~and fire intensity F~~median fire radiative power ~~using FRP as proxy (in MW)~~ from~~or~~ FRY database (derived from MCD64A1 with a cut-off of 14 days), and percentage of burned area each year (from GFED). ~~in the patch reconstruction algorithm.~~



F~~i~~igure 2: Median fire size~~FS~~ vs ~~F~~fire radiative power (FRP in MW) for different GFED regions. The error bars represent the 25th and 75th quantiles of the FS distribution. The color of the dots and error bars represent the mean burn date of fire patches in each ~~FI~~FRP bin. The black line shows the interpolated 4 degrees polynomial used to smooth the value of FRP associated with maximum median fire size. The background histograms represent the number of fire patches in each FRP bins.

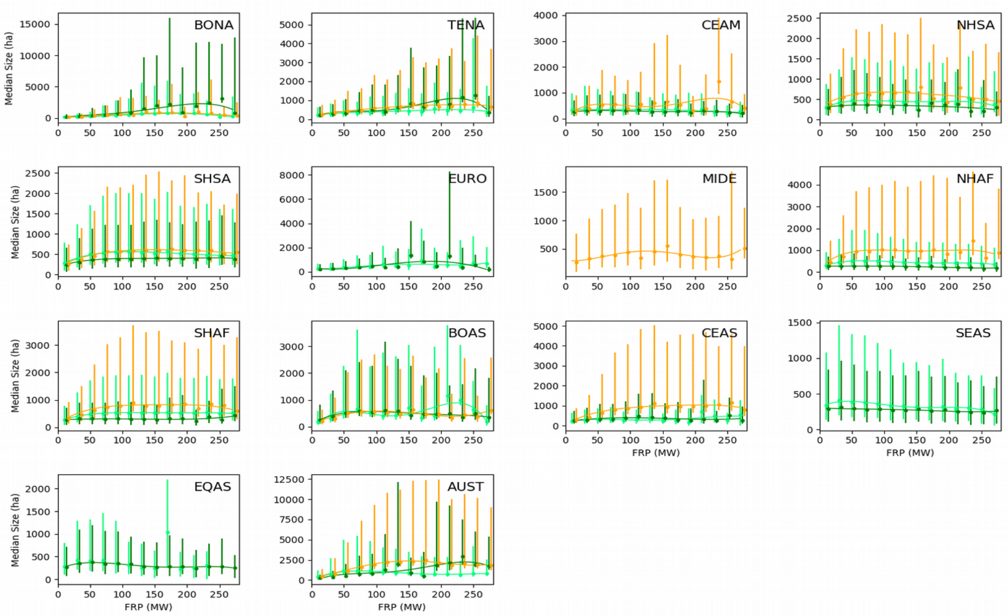


Figure 3: Median fire size vs ~~FRP~~fire radiative power (FRP) for different GFED regions for savannas (light green), forests (dark green) and grassland/shrubland (orange). These vegetation classes are obtained by grouping similar land cover type from MODIS Land Cover data, and their spatial extent can be found in Supplementary. The error bars represent the 25th and 75th quantiles of the FS distribution. The color lines show the interpolated 4 degrees polynomial used to smooth the value of FRP associated with maximum median fire size for each land cover type.

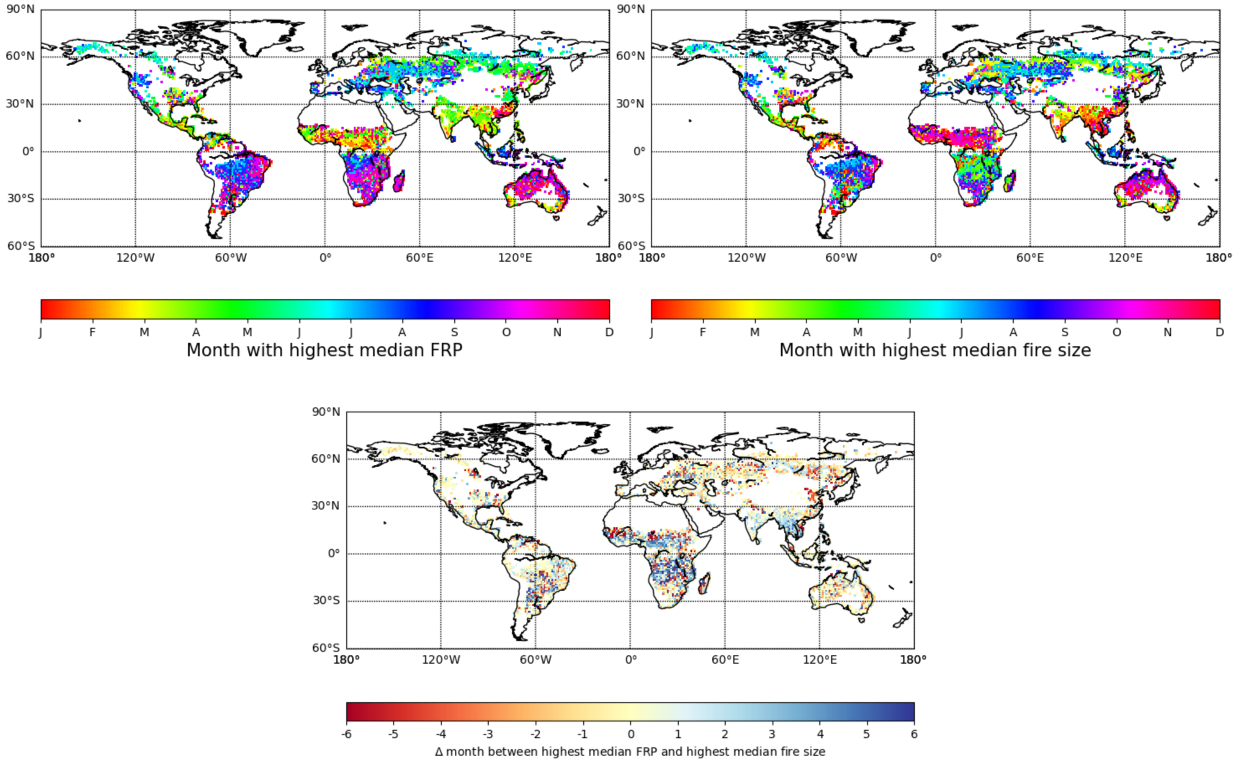


Figure 4: Month with highest median ~~FRP~~fire radiative power (FRP, ~~(~~top left), highest median FS (top right), and the difference between the two (bottom). In blue cells, the month with the largest fires events happen before the month with the most intense fires. In red cells, the month with the largest fires events happen before the month with the most intense fires. In yellow cells, the months with the largest fires and with the most intense fires are the same.

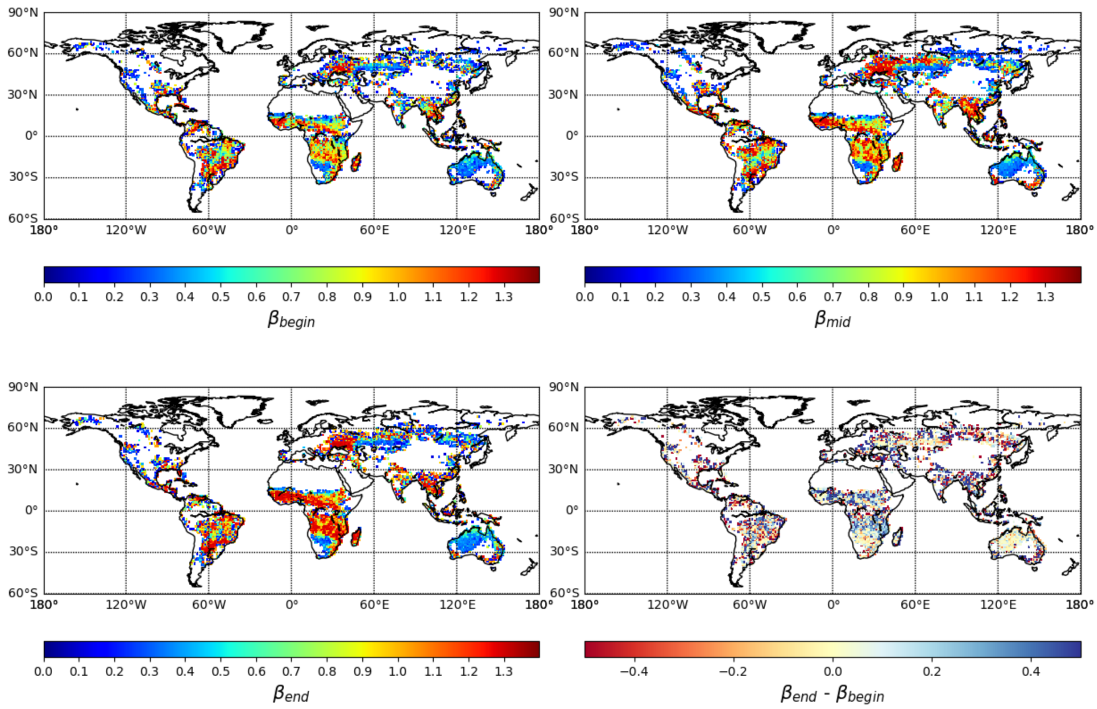


Figure 5: Value of the log-log scale slope of the fire size distribution at the beginning of the fire season, beta (4 months before the month with the highest amount of BA), in the middle of the fire season (corresponding to the month with the highest BA) and at the end of the fire season (4 months after the month with highest BA).

Vegetation type	GFED Region	FRP with largest associated fire patch sizes (MW)	Slope of the FRP vs median FS relationship before max FS ($ha.MW^{-1}$)	Slope of the FRP vs median FS relationship after max FS ($ha.MW^{-1}$)
Savannas	BONA	175	3.907	-7.791
	TENA	221	1.179	-1.974
	CEAM	10	2.342	-0.499
	NHSA	74	2.813	-0.400
	SHSA	110	2.692	-0.661
	EURO	270	1.548	NA
	NHAF	67	5.256	-0.662
	SHAF	110	2.300	-0.172
	BOAS	224	2.149	-19.993
	CEAS	260	0.577	1.011
	SEAS	45	3.865	-0.575
	EQAS	185	1.716	2.038
	AUST	75	13.665	-1.684
Forests	BONA	220	9.204	-39.657
	TENA	222	3.404	-19.811
	CEAM	57	1.071	-0.382
	NHSA	76	1.288	-0.457
	SHSA	242	0.494	-3.859
	EURO	185	4.979	-6.128
	NHAF	68	0.609	-0.508
	SHAF	270	0.076	NA
	BOAS	88	5.734	-1.075
	CEAS	90	1.421	-0.696
	SEAS	10	3.865	-0.224
	EQAS	55	2.904	-0.395
	AUST	237	9.533	-8.085
Grasslands/shrublands	BONA	170	5.239	-1.579
	TENA	219	2.342	-2.809
	CEAM	230	2.003	-11.986
	NHSA	100	3.014	-1.451
	SHSA	148	2.700	-0.726
	MIDE	270	0.136	NA
	NHAF	220	1.329	-13.382
	SHAF	170	2.939	-2.049
	BOAS	105	5.081	-0.402

	CEAS	208	3.725	-2.341
	AUST	149	16.639	-4.785
All	BONA	196	4.420	-7.817
	TENA	215	1.359	-1.513
	CEAM	84	0.775	-0.154
	NHSA	83	2.318	-0.637
	SHSA	105	2.384	-0.237
	EURO	239	0.628	-8.143
	MIDE	198	0.553	-1.254
	NHAF	71	3.939	-0.683
	SHAF	116	2.474	-0.115
	BOAS	86	3.409	-0.346
	CEAS	277	0.613	NA
	SEAS	37	3.906	-0.327
	EQAS	60	3.112	-0.187
	AUST	142	9.169	-0.523

Table 1 : Value of the ~~FI~~FRP threshold at maximum median FS, and the slope of FS vs ~~FI~~FRP before the threshold value for different GFED regions.