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International Journal of Wildland Fire

Supplementary Material

Disentangling the factors of spatio-temporal patterns of wildfire activity in south-eastern France

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1. Supplementary material

S1. Description of the study area

The Mediterranean French area has a wide variety of climatic regions (see also Fig. A1 for the SylvoEcoRegions), in Fig. S1.1 we show some examples (for the year 2015) geographically scattered in the area. Overall, precipitation is more common during the colder months, and reduced during the warmer months. Maximal temperatures vary approximately from +40ºC to +25ºC, and minimal temperatures reach locally to -20ºC.

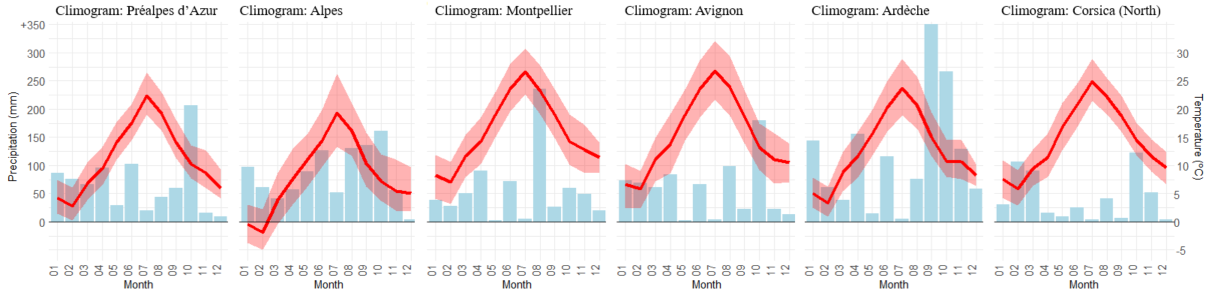


Fig. S1.1: Climograms for the year 2015 corresponding to six SAFRAN pixels located throughout the study area. In order of appearance: Préalpes d'Azur (pixel 8528), Alpes (pixel 7653), Montpellier (pixel 8858), Avignon (pixel 8507), Ardèche (pixel 7794), Corsica (pixel 9638). Precipitation represented in blue columns. Temperature represented with a red line and the maximal-minimal monthly temperature interval.

The spatial distribution of wildland area (Fig. S1.2A) and population (Fig. S1.2B) follow inversed patterns, with few settlements merged between the natural lands. Instead, population gets concentrated near the coast and allong the Rhone river valley.

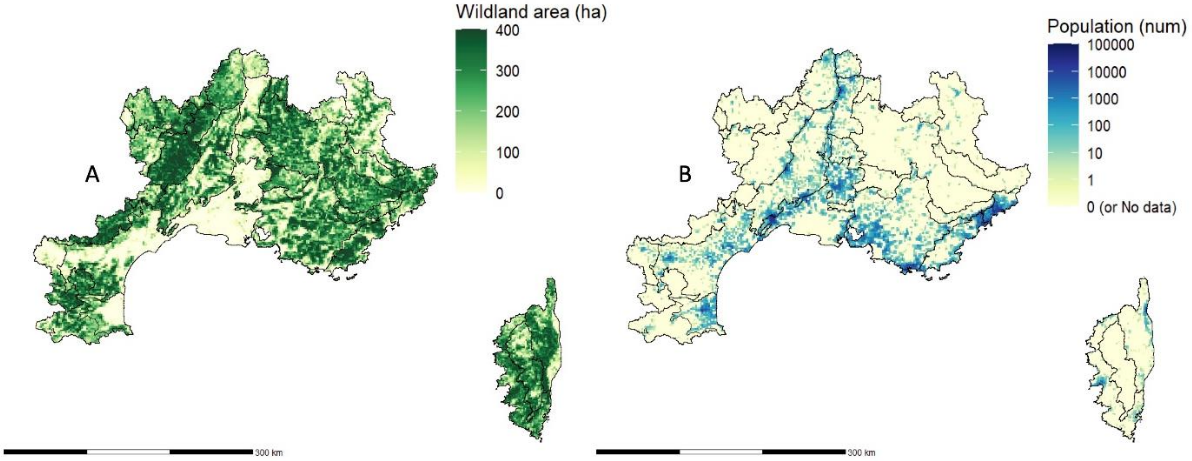


Fig. S1.2: Spatial distribution of Wildland area (A) and inhabitants per pixel (B) inside the study area. Represented in the 2km DFCI grid.

S2. Overview of Firelihood FL1 specifications and estimation (Pimont et al. 2021)

Firelihood is a Bayesian probabilistic framework described in details in Pimont et al. (2021). The model belongs to the class of Generalized Additive Mixed Models (GAMMs). The occurrence component is a Poisson model which predicts the number of fires (N_i) per SAFRAN's pixel and per days:

$$\log N_i \sim \log(WA) + f_{FWI}(FWI_i) + f_{WEEK}(WEEK_i) + \beta(Year > 2003) + f_{X,Y}(X_i, Y_i) \qquad \text{(eq.S1)}$$

The explanatory variables were the wildland area (WA) and the FWI. The model had an offset $\log(WA_i)$, a temporal component based on the weekly correction, a post 2003 effect and a spatial component based on the geographical pixel coordinates.

The nonlinear f-functions in the equations are modelled with piecewise constant first-order random walks (rw1) with a fixed number of classes (the above-mentioned intervals) corresponding to a transformation of the continuous variables into discrete classes (categorical variables). One hyperparameter (called *precision*) governs curve smoothness (i.e., the size of the small steps between consecutive segments). For the two-dimensional predictors (X,Y) of the spatial effect, FL1 uses the SPDE approach to provide a numerically convenient representation of the spatial Matérn covariance function. It is applied to a triangulation mesh of the 2D space and specifies a prior distribution corresponding to a Gaussian random field over 2D space, and a the SPDE approach is used. Two hyperparameters are estimated for this random field: precision (to control the spatial variability of field values) and range (to control spatial dependence, *i.e.* the smoothness of the piecewise linear spatial surface).

Estimation is carried out with the integrated nested Laplace approximation (INLA), which is appropriate for regression models with Gaussian process priors for random effects as in our setting. It uses fast and accurate deterministic approximations of the components of the "posterior model", which is estimated by combining the prior model with the observed data thanks to the famous Bayes theorem. INLA output allows simulation from the posterior model, where the stochastic nature of the posterior model is preserved and allows for accurate uncertainty assessments in the applications.

For each simulated fire, its size is predicted from a complex piecewise modelling of the size distribution which built up on three exceedance thresholds (10, 100 abs 1000ha) and Pareto and Generalized Pareto distributions. Three exceedance thresholds are modelled as a probability $p_i^u$of a given predicted fire i to exceed a certain size u:

$$log \frac{p_i^u}{1 - p_i^u} = \beta_0^{p,u} + f_{WA}^{p,u} + f_{FWI}^{p,u} \qquad \text{(eq.S2)}$$

The modelling of piecewise Pareto and Generalized Pareto distributions is not reported here, as these components of the *Firelihood* -which allows to simulate burnt areas- have not been modified in the present work, but all details are provided in Pimont et al. (2021). These models were estimated with the same modelling approach as described above for the occurrence component.

S3. Partition of effects involved in spatial patterns

The estimation of relative contribution of FWI, LULC and unexplained spatio-temporal effect to spatial distributions of fire activities can be obtained by partitioning the spatial variance of simulations of the log number of fires, thanks to the additivity of the Poisson process.

If we sum the expected fires of a given year *y* in pixel *i*, we can write:

$$logN_{i,y}^{1ha} = log\left(\sum_{d\ in\ year\ y} N_{i,d}^{1ha}\right) \quad \text{(eq.S3)}$$

Since LULC and spatio-temporal terms are constant for pixel *i* and year *y*, we can factorize them:

$$\begin{aligned} logN_{i,y}^{1ha} &= \beta_0 + log\left(\underbrace{\sum_{d\ in\ year\ y} e^{f_{FWI}(FWI_{i,d})+f_{WEEK}(WEEK_{i,d})}}_{\lambda_{i,y}^{FWI}}\right) \\ &+ log\left(\underbrace{e^{\beta(WAp_{i,y})+\sum_{LULCM} f_{LULCM}(LULCM_{i,y})}}_{\lambda_{i,y}^{LULCM}}\right) \\ &+ log\left(\underbrace{e^{f_{X,Y}(X_i,Y_i)+f_{YEAR}(y)+f'_{X,Y}(X_i,Y_i)(y-1992)}}_{\lambda_{i,y}^{Spatio-temporal}}\right) \end{aligned} \quad \text{(eq.S4)}$$

So that, $logN_{i,y}^{1ha} \propto log(\lambda_{i,y}^{FWI}) + log(\lambda_{i,y}^{LULCM}) + log\left(\lambda_{i,y}^{Spatio-temporal}\right)$

We then propose to estimate the relative contribution (RC) percentage of each component as:

$$\begin{aligned} RC_{FWI}^{1ha} &= 100\,\frac{\overline{var_i\left(log(\lambda_{i,y}^{FWI})\right)}^{y}}{\Delta} \\ RC_{LULCM}^{1ha} &= 100\,\frac{\overline{var_i\left(log(\lambda_{i,y}^{LULCM})\right)}^{y}}{\Delta} \\ RC_{Spatio-temporal}^{1ha} &= 100\,\frac{\overline{var_i\left(log(\lambda_{i,y}^{Spatio-temporal})\right)}^{y}}{\Delta} \end{aligned} \quad \text{(eq.S5)}$$

Where var_i is the variance over all pixels i and the bar denotes the average over years and $\Delta = \overline{var_i\left(log(\lambda_{i,y}^{FWI})\right)}^{y} + \overline{var_i\left(log(\lambda_{i,y}^{LULCM})\right)}^{y} + \overline{var_i\left(log(\lambda_{i,y}^{Spatio-temporal})\right)}^{y}$

For 10 and 100 ha, we applied a similar methodology (for 100 ha):

$$logN_{i,y}^{100ha} = log\left(\sum_{d\ in\ year\ y} N_{i,d}^{1ha}\, p_{i,d}^{u}\right) \quad \text{(eq.S6)}$$

Assuming that $p_{i,d}^{u}$ is small, we can write:

$$p_{i,d}^{u} \approx e^{\beta_0^{p,u} + f_{FWI}^{p,u}(FWI_{i,d}) + \sum_{LULCMs} f_{LULCM}^{p,u}(LULCM_{i,y}) + f_{YEAR}^{p,u}(y) + f_{BESAG}^{p,u}(SER)}$$

Grouping together terms varying on the daily basis (FWI terms for occurrence and exceedance and seasonal corrections):

$$\begin{aligned} logN_{i,y}^{100ha} &= log\left(\sum_{d\ in\ year\ y} N_{i,d}^{1ha}\, p_{i,d}^{u}\right) \quad \text{(eq.S7)} \\ &= \beta_0 + \beta_0^{p,u} + log\left(\underbrace{\sum_{d\ in\ year\ y} e^{f_{FWI}(FWI_{i,d}) + f_{WEEK}(WEEK_{i,d}) + f_{FWI}^{p,u}(FWI_{i,d})}}_{\lambda_{i,y}^{FWI}}\right) \\ &+ log\left(\underbrace{e^{\beta(WAp_{i,y}) + \sum_{LULCM} f_{LULCM}(LULCM_{i,y}) + f_{LULCM}^{p,u}(LULCM_{i,y})}}_{\lambda_{i,y}^{LULCM}}\right) \\ &+ log\left(\underbrace{e^{f_{X,Y}(X_i,Y_i) + f_{YEAR}(y) + f'_{X,Y}(X_i,Y_i)(y-1992) + f_{YEAR}^{p,u}(y) + f_{BESAG}^{p,u}(SER)}}_{\lambda_{i,y}^{Spatio-temporal}}\right) \end{aligned}$$

So that the same metrics for relative contribution can be built for $logN_{i,y}^{100ha}$ and $logN_{i,y}^{10ha}$ than for $logN_{i,y}^{1ha}$.

S4. Distribution and changes of Land-Use and Land-Cover by SylvoEcoRegion in the Promethee area.

The French Mediterranean landscape has been dynamic over the study period. Here we illustrate the observed changes in terms of Land-Use and Land-Cover (LULC) from 1993 to 2018, represented as the mean area per pixel within each SylcoEcoRegion (SER) in figures S4.1 and S4.2.

The largest changes do not exceed the 45ha in average per pixel of 400ha, although those largest magnitudes are only seen in single SERs. Shrubland area (Fig. S4.1 A – B) and agricultural area (Fig. S4.2 K – L) have suffered the most extended loses; while urban (Fig. S4.1 E – F), mixed forest (Fig. S4.2 G – H) and broadleaved forest (Fig. S4.2 I – J) areas have the largest extent of positive change.

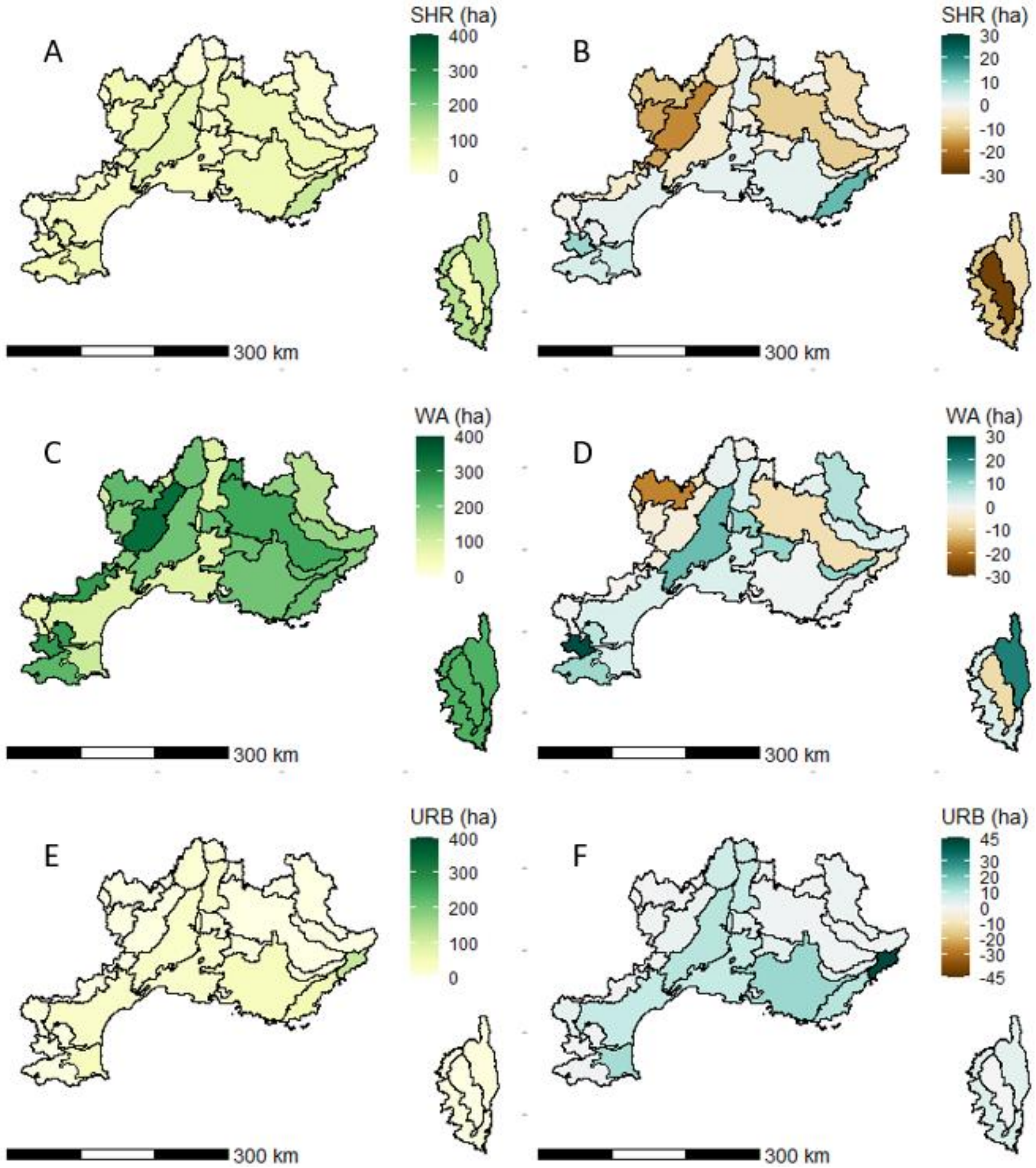


Fig. S4.1: Distribution of mean area per pixel of LULC variables by SERs in 1993 (left column) and their total absolute change in mean area per pixel for the period 1993-2018. Where: SHR = shrubland area; WA = wildland area: URB = urban area.

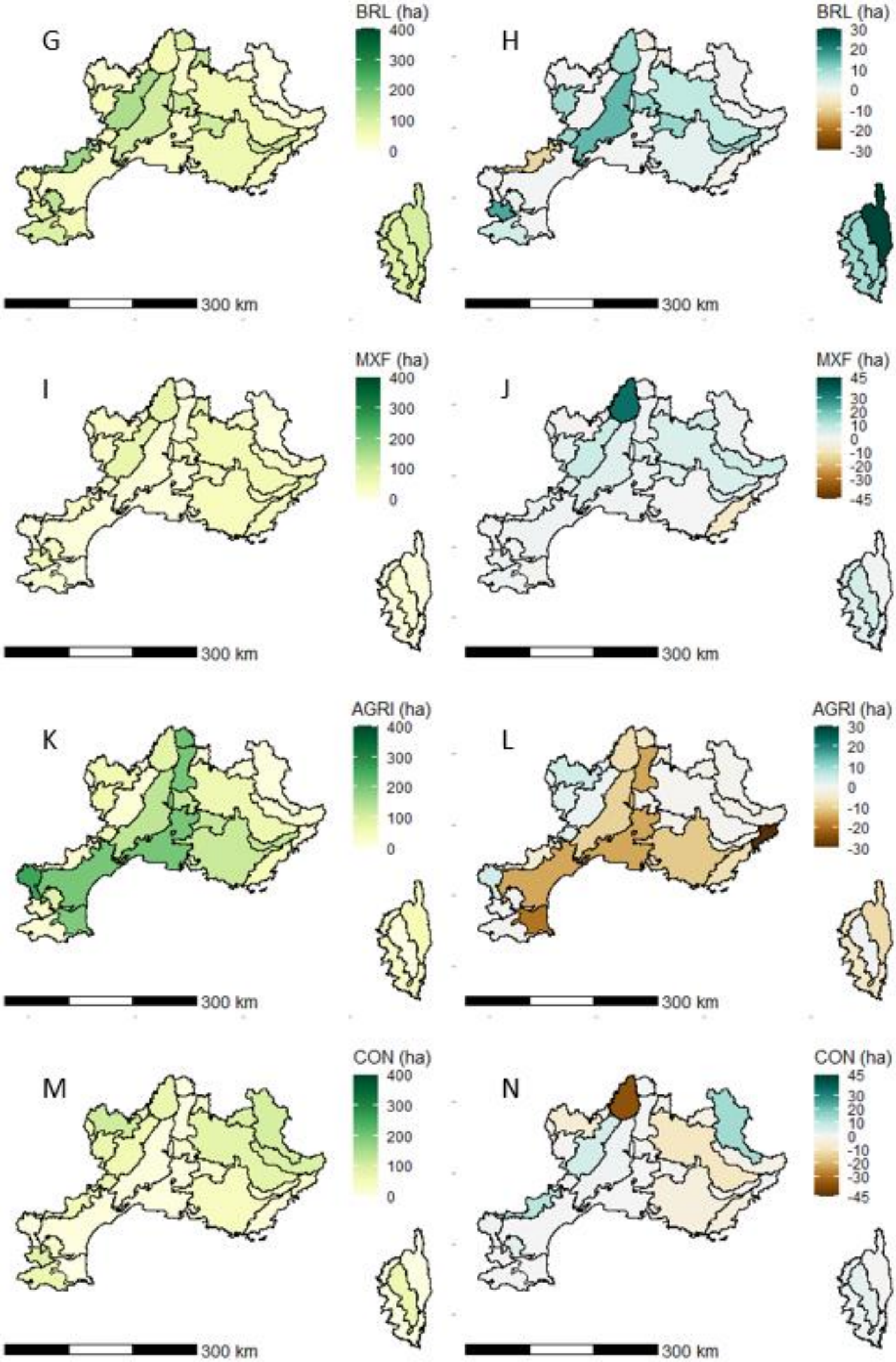
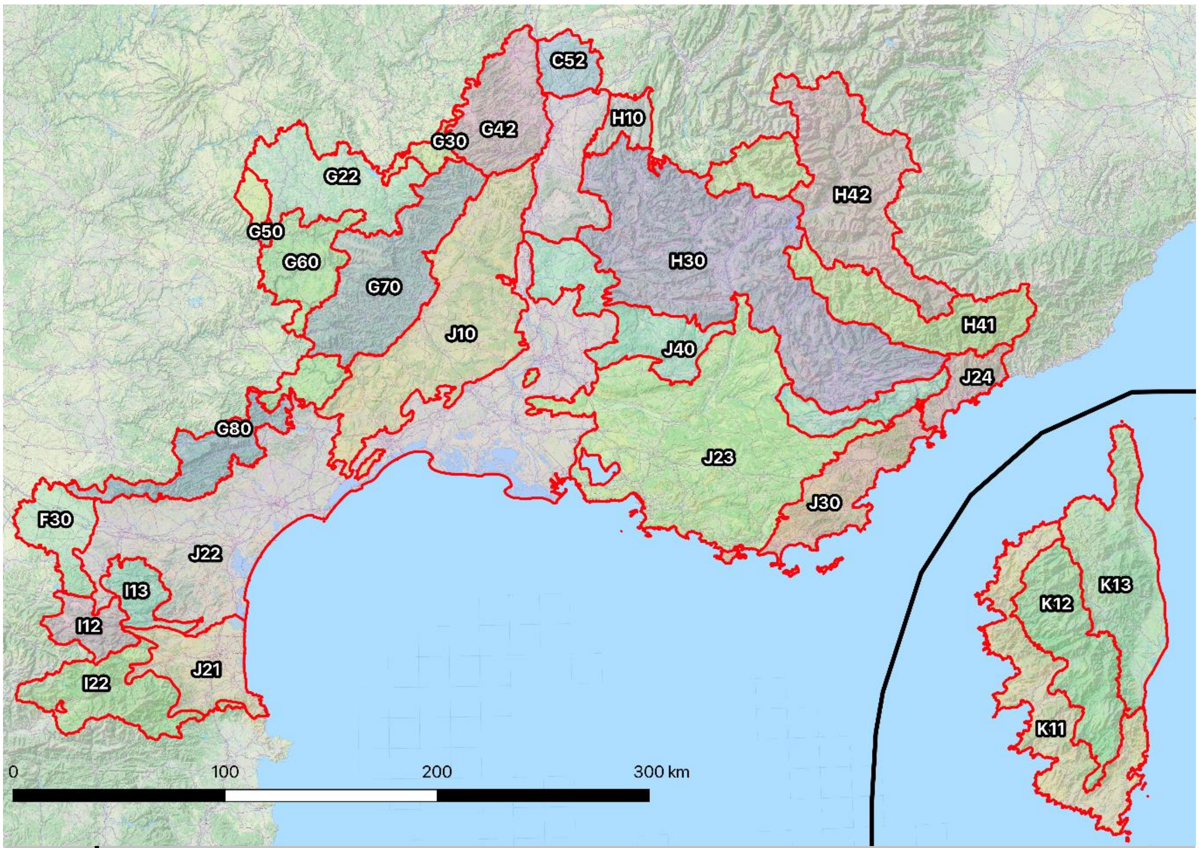


Fig. S4.2: Continuation: Fig S4.1. Where BRL = broadleaved forest area; MXF = mixed forest area; AGRI = agricultural area; CON = coniferous forest area.

Additional figures



Code	Nom (Français)	Name (if translation is possible)
K11	Corse occidentale	West Corsica
K12	Montagne corse	Mountaiins of Corsica
K13	Corse orientale	East Corsica
G42	Monts du Vivarais et du Pilat	-
F30	Coteaux de la Garonne	Hillsides of Garonne river
H41	Alpes intermédiaires du Sud	Southern Mid-Alps
H42	Alpes internes du Sud	Southern Inner-Alps
I13	Corbières	-
G50	Ségala et Châtaigneraie auvergnate	-
I12	Pyrénées cathares	Cathare Pyrenees
J23	Provence calcaire	Sandstone Provence
J10	Garrigues	-
J24	Secteurs niçois et préligure	Nice and preligure sectors
G60	Grands Causses	-
I21	Haute-chaîne pyrénéenne	Upper pyrenean chain
I22	Pyrénées catalanes	Catalan Pyrenees
J21	Roussillon	-
G70	Cévennes	-
H10	Préalpes du Nord	Northern Pre-Alps
J22	Plaines et collines rhodaniennes et languedociennes	Rhone and Languedoc plains and hills
J30	Maures et Esterel	-
G22	Plateaux granitiques du centre du Massif central	Granite plateaus in the center of the Massif Central
G80	Haut-Languedoc et Lévézou	Upper Languedoc and Lévézou
H22	Alpes internes du Nord	Northern Inner-Alps
C52	Plaines et piémonts alpins	Alpine plains and foothills
G30	Massif central volcanique	Volcanic Massif Central
J40	Préalpes du Sud	Southern Pre-Alpes
H30	Alpes externes du Sud	Southern Outer-Alpes

Fig. A1. Map of the 28 Sylvo-Eco-Regions (SER) of the study area with the key code and name. The perimeter of the shape corresponds to the border Promethee zone.

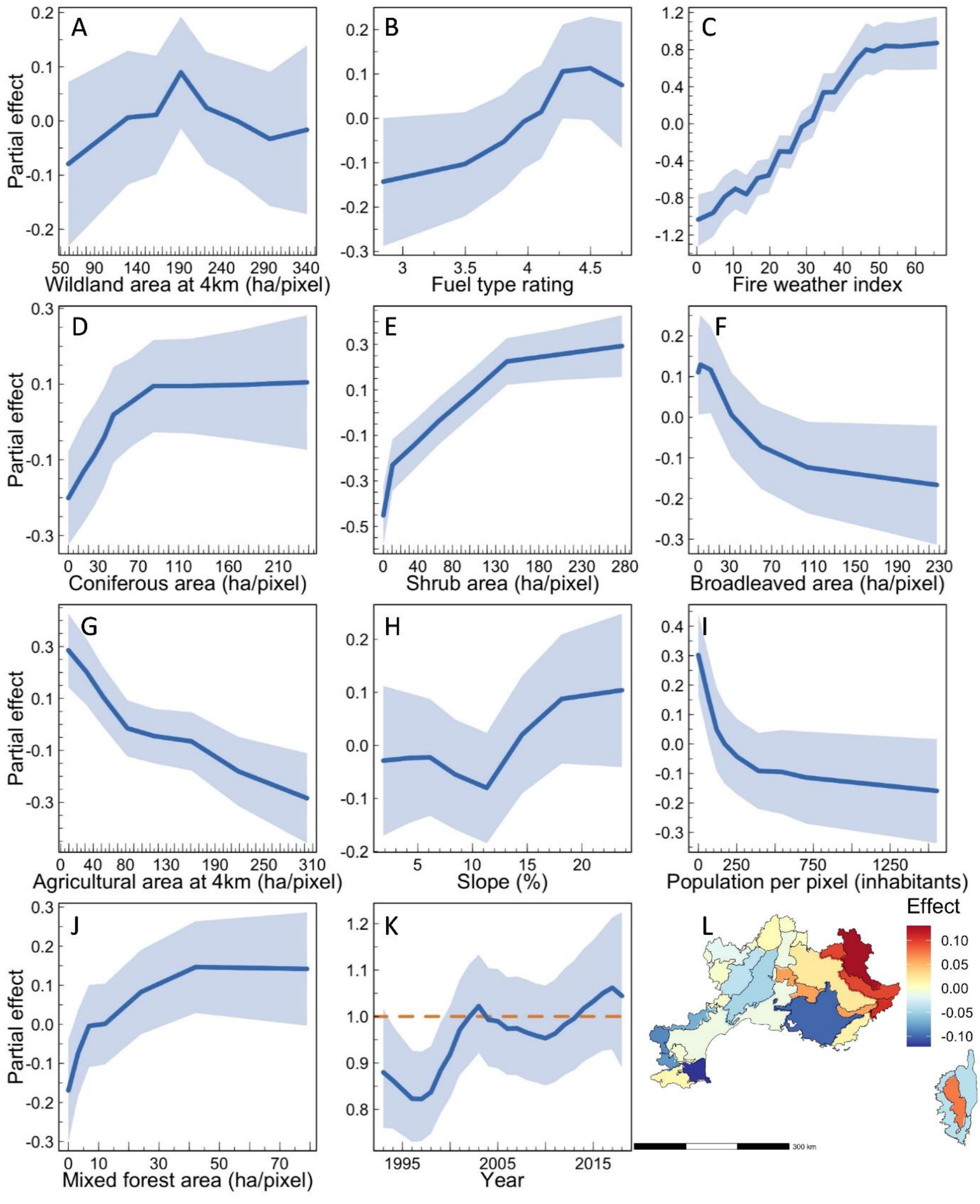


Fig. A2. Partial effects of the predictor variables for the 10ha exceedance probability model intervals; the X axis shows the value in each pixel but only inside the 95% of the data distribution, cutting the extreme values from below and above; the Y axis, Partial effect, is the contribution of fire the predictor variable's value to the probability of exceedance. And the spatial effect of the SylvoEcoRegions. Spatial effect from the Besag component in the 10ha exceedance model. The magnitude effect is drawn in a color coding in each pixel, the labels inside each polygon (thin black lines) corresponds to the code of the SylvoEcoRegions. The magnitude of the effect will be positive when the model underpredicts the exceedance probability, and negative when the model overpredicts this probability.

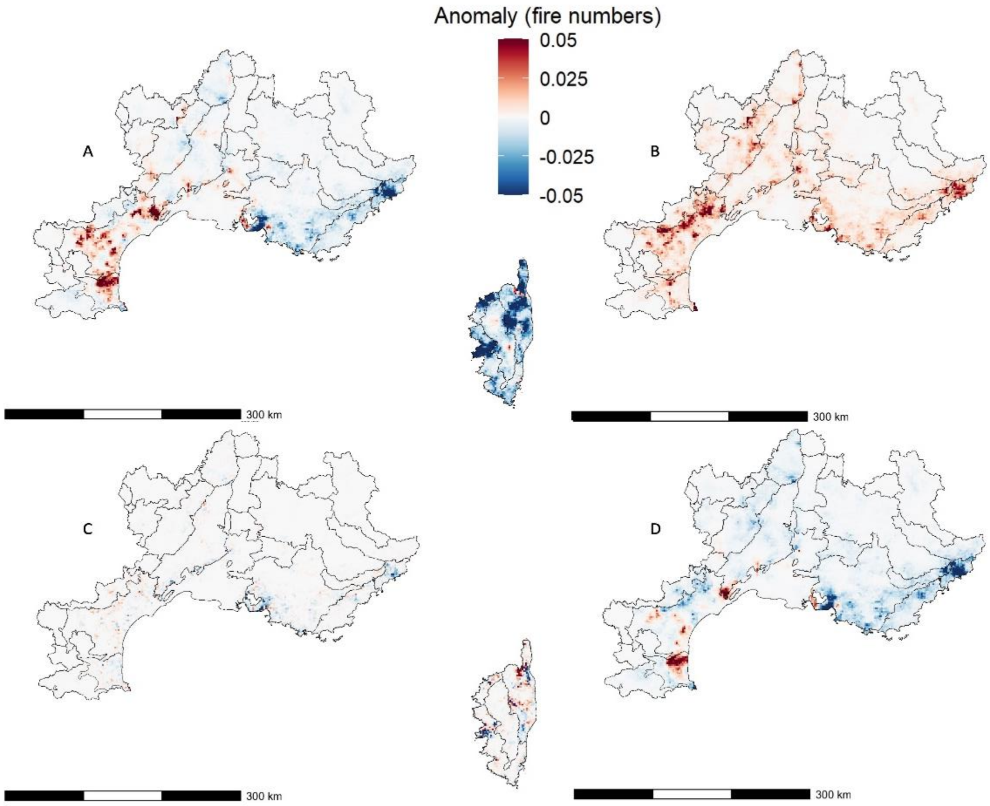


Fig. A3. Spatial distribution of the changes (anomalies) between the first and second decades of the comparison. For illustration porpoises, here represented the scenarios for 10ha fires.

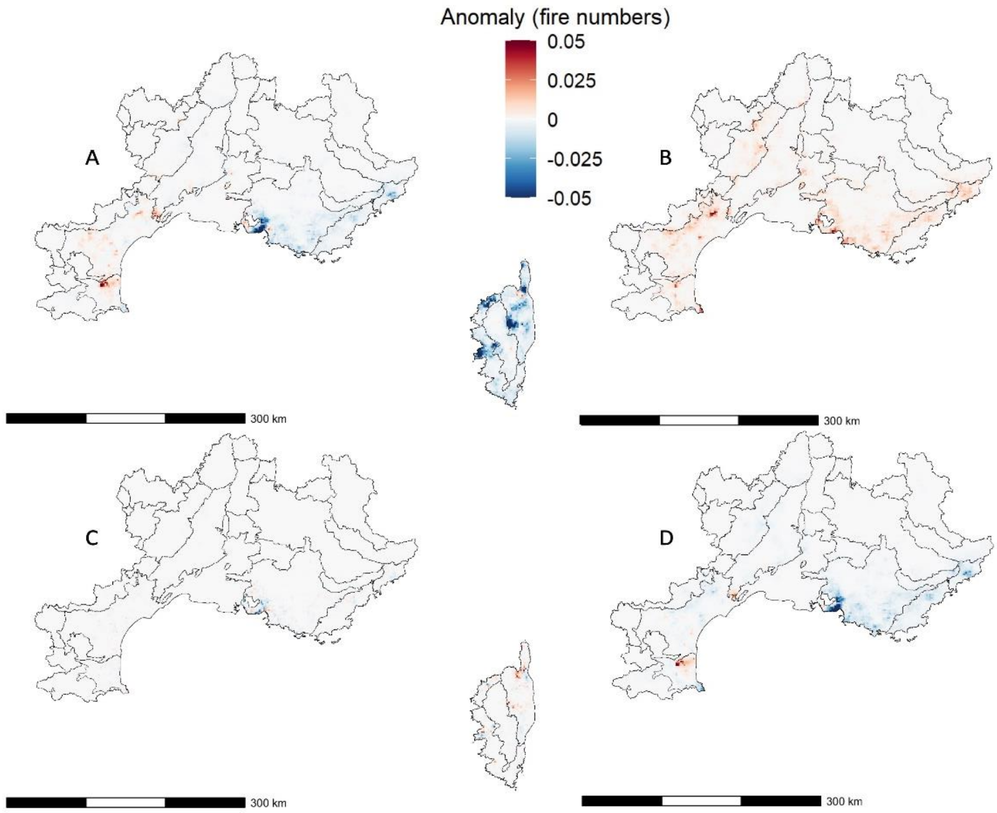


Fig. A4. Spatial distribution of the changes (anomalies) between the first and second decades of the comparison. For illustration porpoises, here represented the scenarios for 100ha fires.

To the Editor-in-chief of the International Journal of Wildland Fire

Dr. Susan G. Conard

Dear editor,

We have received the feedback on our manuscript “Wildfire spatial patterns – not their changes – are driven by fire-weather, land-use and land-cover factors for consideration in International Journal of Wildland Fires as part of the ICFFR special issue. Following the comments by the two reviewers and editors, we provide here a revised version. We treated carefully the comments and made our best to follow the recommendations while staying within the journal’s guidelines. Please also note that following the comment of reviewer, we also changed the title of manuscript, which now reads : “Disentangling the factors of spatio-temporal patterns of wildfire activity on Mediterranean France”. We are confident that these corrections have much improved the manuscript, and we hope you will consider this final version suitable for publication in International Journal of Wildland Fire.

Thank you for your consideration.

Yours sincerely,

On the behalf of the authors, Jorge Castel-Clavera

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Editor's Comments to Author:

Please consider some increases in color intensity for your background maps. The yellow is quite pale. It could be helped by outlining the perimeter. You also may wish to consider how well these figures will show up in gray-scale. Since our recommendation is for relatively minor revision, I recommend that you submit the final files needed for production, as described in the information for authors and the attached file below. I do note that your reference list is not fully in IJWF format. This would be the time to correct that. In general, the document text should be in a word file, including tables and heading and a list of figure captions. Each figure should be in a separate file. Refer to information online for more detail. Files can then be combined within ScholarOne into a pdf for review.

Regarding the modifications to the figures, we have changed the final form of the maps. Outlines and internal borders (corresponding to the SylvoEcoRegions used in the study) are added to all maps, in addition the colour scale is changed for a clearer one.

The format of the file is changed to suit the requirements.

Associate Editor

Comments to the Author:

This manuscript explores fire activity patterns observed in Mediterranean France, using Bayesian spatio-temporal modelling to determine the relative contributions of climatic and non-climatic drivers. The paper is interesting and I a recommend acceptance after moderate revisions.

Does Firelihood (FL) separate lightning-caused fires from human-caused fires as the ignition processes are quite different?

FL does not separate lightning-caused fires from human-caused fires, the reason being the distinction between lightning-caused and human-caused fires in this region would not be justified (as it is for example in North America) because of the low occurrence of lighting fires (less than 5% of ignitions) (Ganteaume et al., 2013). In addition, the database we are using has too much information gaps in this regard.

The results for 2-km performed better than 4-16 km, did you consider 1km grid?

Unfortunately, we cannot consider finer resolution for the FL model at the moment. Indeed, the location of fire ignitions is recorded in the fire database in a 2km*2km grid (i.e. geographical coordinates are not specified). In addition, the 2km grid is a good trade-off between coarser pixels and computational demands (mind that there are more than 20.000 pixels).

Missing yearly data -Line 181, how much missing data was there? Interpolation for missing years could be a problem.

The missing data refers only to the years between the intervals of released LULC data, especially the Corine Land Cover product from Europe's Copernicus data, we did not encounter gaps in other temporal scales or spatially. We agree that the linear interpolation between years with available data is not the most accurate approach, because the LULC changes usually happen in a sudden manner; but keeping static data in 6-year intervals and having a sudden change periodically and for all pixels at the same time is surely less representative of reality. In addition, no precise information about the temporality of changes was available for us. Finally, the magnitude of the changes is very small over all so, assuming a smoothed progression will avoid attributing changes in the incorrect years while being still representative of reality.

The role of fire in LULC needs to be addressed or discussed as it could complicate the analysis.

We recognize that fires may modify the land cover depending on the initial land cover and fire severity, and reduce fuel loads for some years. But we stress that the total yearly burnt area represents a very small proportion of the total wildland area in the region (well below 0.5% area burnt at regional scale, usually less than 1% at local scale).
Moreover, the most significant fire-induced changes in land cover are reflected in the next Corine Land Cover inventory (update). It is true however that small burnt areas and low severity fires are not captured by this inventory: the Corine Land Cover provided by Copernicus Land Monitoring Service has a spatial resolution of 25 ha (see: https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=metadata), the canopy layer must have been burnt almost completely, so, surface fires that do not remove the canopies will not be detected, and the fire must happen the year before or the same year the data is collected, in other cases, regeneration may take place before the fire is detected and included in the database.

The English needs to be tightened up and both reviewers have suggestions to address the presentation as well as many other comments that need to be addressed.

Minor comments

Barros and Ferreira 2009 in text and not in references
Oliveira et al. 2012 in text but not in references

Done

L569 Rodriguez et al. 2014 should start on a new line

Done

Might be interesting to conduct this analysis included the 2022 fire season when available.

We surely would like to introduce the last fire events in our analysis, but for the time being the data concerning the last season has not been released. It is already clear that this year 2022 has been rather exceptional in fire activity at national scale, due to the heatwaves and the sustained drought we have suffered before and during the fire season, but it is not sure that it was so exceptional for the south-east of France.

Reviewers' Comments to Author:

We thank both reviewers for their contributions, in the following we address the individual comments in order of appearance in the text.

Reviewer 1:

Comments to the Author:

This manuscript presents a sophisticated and comprehensive analysis of wildfire occurrence analysis showing a new iteration of the Firelihood model. The method is very interesting and adds new capabilities, such as the possibility to account for temporal and spatial random effects. Overall, the manuscript is well written and structured. I recommend it for publication after addressing a number of issues and questions which I include in the attached file: "WF22086_Proof_hi.pdf"

Line 22 (reviewer 1): landscape is too generic, specify variables or features identified

We changed this expression to some specific examples. It now reads “(i.e., orography, land cover and human activities)”

Line 28 (reviewer 1): patterns

Done

Line 28 (reviewer 1): this cannot be directly concluded, it is a hypothesis based on the unexplained variance

Agreed. We made it clear that it is a hypothesis and not a conclusion

Line 43 (reviewer 1): Deleted favourable. Ignition source. Perhaps is best referring to suppression and mitigation policies

Done, this sounds indeed clearer.

Line 49 (reviewer 1): consider including the following works:
https://doi.org/10.1016/j.apgeog.2014.04.002 https://doi.org/10.1016/j.jenvman.2018.07.098

There are already two references supporting our information, one being very recent. Thank you for the contribution, we will take it into account in our following work. Nonetheless, your suggestion for Rodrigues et al. (2018) will be used later as an example regarding a previous comment in this review.

Line 57 (reviewer 1): The reference to Ganteaume et al. 2013 is more appropriate here

Done

Line 68 (reviewer 1): severe

Done

Line 72 (reviewer 1): consider adding:

10.5194/nhess-17-1697-2017

Silva, J.M.N., Moreno, M.V., Le Page, Y. et al. Spatiotemporal trends of area burnt in the Iberian Peninsula, 1975–2013. Reg Environ Change 19, 515–527 (2019). https://doi.org/10.1007/s10113-018-1415-6

Nunes, L., Álvarez-González, J., Alberdi, I. et al. Analysis of the occurrence of wildfires in the Iberian Peninsula based on harmonised data from national forest inventories. Annals of Forest Science 76, 27 (2019). https://doi.org/10.1007/s13595-019-0811-5

Thank you for these suggestions. We added Silva et al. (2019) as an example for comparison with other regions in line 74.

Line 93 (reviewer 1): consider replacing region with northely

Done

Line 95 (reviewer 1): highly influential

Done

Line 98 (reviewer 1): lower fire activity (despite local hot-spots)

Done

Line 114 (reviewer 1): if so

Done

Line 115 (reviewer 1): relevant

Done

Line 136 (reviewer 1): is it only unknown factors or also the degree of stochasticity of the phenomena?

First, we emphasize that the model is already designed to deal with the stochasticity of the random processes at play for the day-pixel resolution (see lines 123-124, with the Poisson distribution for occurrence, probabilities of exceedance above increasingly high thresholds and distributions for fire sizes within the corresponding size intervals). The unknown factors or unexplained variability also contribute to this stochasticity, and sometimes these factors show autocorrelations over space and time, which we consider through the structure of the spatiotemporal effect we estimated. Another source of uncertainty is purely statistical and arises from the estimated parameters (whose true values are unknown). Therefore, by sampling from the posterior distribution (see Appendix S2 as well as Pimont et al. 2021 and Koh et al 2022 for more details), we allow for stochasticity in the spatiotemporal effects due to statistical uncertainty and other spatiotemporally correlated sources of uncertainty. In the paper, we now mention that spatiotemporal effects "introduce additional stochasticity into the model to appropriately capture variability due to unknown factors and statistical uncertainty" (see lines 132-133). The lack of knowledge about, or unavailability, of unaccounted factors produces a lack of accuracy, but which could of course be further reduced if we succeed in including more explanatory factors.

Line 140 (reviewer 1): during the compilation period. We do not know whether a given non-burned pixel was fire-affected in the past. This contributes to the stochasticity and led to define terms like pseudo-background observations (https://doi.org/http://dx.doi.org/10.1071/WF11178

This is a very interesting point. We added "during the observation period" to the sentence. However, we did not include the reference as we model fire activity at the daily scale (in this case pixels are truly either burned or not burned a given day) contrary to Bar Massada et al. 2013 who worked on ignition distribution modelling (without consideration of time), which makes the concept of pseudo absence mandatory (because absence may depend on the duration of observation period).

Fig 1: (reviewer 1): consider using interval classes to map fire occurrence and add administrative boundaries to enrich the map. Also, use a specifically-devoted interval to show non-burned locations during the study period.

The legend of this figure was modified, so it clears out the pixels where there are no observations during the study period, although due to the sparseness and rarity of the fire events, the discretisation of the observation in interval classes would introduce confusion on the real distribution of fire activities, so the continuous scale is maintained.

We included the borders for the SylvoEcoRegions as for the other maps.

Line 167 (reviewer 1): methods should be written in past tense. Revise

Thanks, we modified the tense in the text.

Line 167 and 175 (reviewer 1): I don't know about the French database but the CLC does not provide yearly data. How was that assign? - You mean you filled missing gaps with a linear function? Land cover changes seldom occur gradually.

CLC data is given, as said in the previous comment, in non-continuous years (4 to 6-year intervals) so to have an approximation of the period in-between we used linear interpolation as a smoothing strategy. Although changes occur in sudden ways, we cannot be sure of the exact year they happen; the fact of keeping sudden changes in a periodic manner does neither represent reality. In addition, the amount of change for those LULC variables in the region and period considered are small, so it is not expected to have a great impact on the method.

Line 217 (reviewer 1): what's the sensitivity of the model to correlated predictors?

First, the prior distributions in our Bayesian framework prevent very high variance of estimators, and they avoid the estimation of the model to break down, even in the case of perfectly correlated predictors. Typically, strong correlation of predictors will lead to higher estimation variance (e.g., larger credible intervals of the parameters controlling the effects of the correlated predictors), and goodness-of-fit criteria such as DIC would tend to show worse performance for the resulting models, that will tend to be "overparametrized". We can also detect potential problems thanks to the analysis of the estimated effects and their posterior uncertainty (e.g. by checking credible intervals).

Line 241-242 (reviewer 1): This deserves a more comprehensive explanation, though perhaps an example of how these scenarios help in understanding attribution may suffice

We improved the explanation to relate the type of variables with the scenarios and clarify that the anomalies are calculated between the real case scenarios and the other three (See lines 219-229). As well we added an exemplified hypothetic result, so in lines 230-234 it reads:

"Anomalies between the scenarios to the reference allowed us to attribute the changes, observed between the two decades (scenario iv), to the different types of explanatory variables, each type corresponding to one of the three first scenarios. For example, if "Fire-weather change" scenario matches the scenario iv it would mean that fire-weather change is responsible for most of the observed changes; this process is supported by the spatial representation of anomalies.”

Line 246-247 (reviewer 1): LULC variables must be investigated carefully to prevent circular logic issues. If a particular land cover change was driven by fire then the explanatory factor is part of the response, hence it will attain higher performance. But the would be misleading from a modelling standpoint.

Your comment is accurate, it is true that a burnt area may imply a change between Land-Use and Land-Cover classes, and due to our linear interpolation (see our response to comment XX above) it could seem that the land change has driven the fire when in fact it is the contrary. Nonetheless, in a practical way we argue that it does not carry any major issue to our study because:

- The effect of LULC variables are estimated over the full database, and not over its changes, so the estimated effects are not susceptible of being perturbed by cyclic phenomena, to which we should add the small size of burnt areas and the proportion they represent from the total wildland area throughout the region.
- Regarding the temporal changes and the assessment of their drivers, the concerned periods are distant and long enough to assume that there very low probabilities of finding confusion sourced by this small cyclic phenomenon.
- Finally, we find important to remind that the spatial resolution of Corine Land Cover is 25ha (no feature in the landscape with a smaller area will be captured in this European database), meaning that most fire events in our time series would not be detected and therefore would not imply any change on the LULC data.

Fig 2 (reviewer 1): The pattern in Fig. 2L mirrors 2K. What does it mean? More elaboration on the spatial and temporal effects is needed.

We disagree with this statement; those two patterns do not mirror each other. In fact, it is complicated to extract direct conclusions from those figures due to the interaction they both have with the annual effect. For this reason, we later decided to include the study of temporal trend based on the simulated scenarios.

Line 277 (reviewer 1): the 16km slope was used here. Is it really meaningful aggregating such a local relief feature at 16km?

We must admit we were surprised but it was statistically more significant, in terms of explanatory power, where 16km slope had the better performance. High slope at 16km might illustrate that we are in a mountainous area (with limited surveillance and access to firefighters), such that predictions work better at this relatively coarser scale of the explanatory variable. Moreover, the bigger fire sizes may be influenced by surrounding pixels, since we do not limit the fires to stay confined in the pixel they are originated, and in this case the largely smoothed slope variable is a good indicator of the rugosity.

Line 291 (reviewer 1): attributing is rather a hard term here. I think talking about preference or something in that line would be better. The fact that one factor dominates does not exclude the remaining factors of being meaningful.

We changed the formulation of this sentence so it does not use hard terms.

Line 292 (reviewer 1): I guess unexplained refers to either temporal or spatial? there is no "unexplained" category in Fig. 4

Yes, we changed it in the text.

Line 296 (reviewer 1): largest fraction

Done

Line 304-305 (reviewer 1): Deleted sentence

Done

Line 312-314 (reviewer 1): perhaps this may be had to be already explained in the methods

This sentence has the objective to introduce the figures with the spatial distribution of anomalies. The methods already explain how the anomalies are calculated and considered.

We improved the method section by mentioning the spatial representations of the anomalies, see answers to Line 236 (reviewer 2) and Line 241-242 (reviewer 1).

Lines 343-345 (reviewer 1): Though I share the criticism to some extent, no al ML-based analysis is conducted under such premises. The approach demonstrated here is valuable in itself.

Thanks for the advice. The lines are deleted.

Lines 348 (reviewer 1): Unexplained reasons does not sound good here. Consider "linked to processes not directly related with the explanatory factors included in the model".

Thanks. It sounds much better.

Lines 403-405 (reviewer 1): something similar has been reported in Spain:

https://doi.org/10.1016/j.scitotenv.2019.13584110.1016/j.envsci.2013.08.005

We added this fact in the discussion.

Lines 416-420 (reviewer 1): I wonder if this can be linked to increased unpredictability of extreme wildfire events.

The unpredictability of extreme events may be a cause of fire-fighting failure in the south-west, leading to an increased burnt area in that part of the region. But we cannot conclude if this is a true or not since in the case of the actual manuscript, we are not focusing on extreme fire events, as this version of *Firelihood* does not aim to model the tail of the size distribution.

Reviewer 2:

Comments to the Author:

Good article but requires editing in terms of writing and to clarify some aspects of the science. Please see attached file: "Review CastelClavera_IJWF_2033.pdf"

Title (reviewer 2)

Not sure why, but I see two titles. One for the main text, and the other is probably for the supplementary material.

We did not realize that the older version of the title was still in the supplementary materials, sorry for this confusion.

I actually like more the second one, and I would just add the region:

"Disentangling the factors of spatio-temporal patterns of wildfire activity on Mediterranean France"

Thank you for this suggestion. We changed the title according to your proposal. “Disentangling the factors of spatio-temporal patterns of wildfire activity in South-eastern France”

We change Mediterranean by South-eastern so it is more consistent with the text.

Summary text (reviewer 2)

"We showed that the impact of recent fire-weather increase has actually caused the increase of fire probability on the western part, but not so in the east

Original: “We showed that the impact of recent fire-weather increase has been overcompensated by a

reduction of escaped-fire probability in the eastern but not in the western part.”

The sentence here proposed gives the same message as in the manuscript, so we switched to this option, but we now also refer to the overcompensation effect, in order to clarify that the phenomenon observed in the east is not just a matter of null-effect of the fire-weather.

Final: “We showed that the impact of recent fire-weather increase has caused the increase of fire probability on the western part, but in the east, it has been overcompensated by a reduction of escaped-fire probability.”

Abstract (reviewer 2)

Key results: Several non-climatic drivers (i.e. landscape) contributed as much as fire-weather to the distribution of fire occurrence (> 1 ha) but less to larger fires (>10, 100 and 1,000 ha). Over the last decades, increased fire-weather should have induced a strong increase in wildfire probabilities. This actually happened on the western part of the region but not so in the east and Corsican Island, most likely due to reinforced suppression policies.

The sentence was adapted according to your proposition, and we also changed the connection between sentences.

While the introduction does a good job of explaining the spatial and temporal factors at play in the Mediterranean and the difficulties of modelling fire due to its rareness, it can read a little choppy due to wordiness, short sentencing, abundance of citations and the placements of these. Some sentences can be merged and some of the references removed, especially those from not peer reviewed publications or in other language not English, leaving only the ones that fit the most to the point being made.

Thanks for this helpful feedback. We changed, merged and deleted some sentences to make the introduction more fluent. We also removed some references that may have some redundancy with others.

One aspect that I think the introduction is missing is a paragraph with some review of what other studies have done to control or account for spatial or temporal effects.

We added this short review starting in the line 82, and it reads:

“Such spatial or temporal effects have been accounted for in a few studies (e.g. Priesler 2004; Woolford 2020) and the interaction between spatial and temporal has recently been addressed by Joseph et al. (2019) and Rodrigues et al. (2018).”

Line40 (reviewer 2): Can be moved down and merged with line49.

Done

Second paragraph can be:

In regions such as the Euro-Mediterranean area (EU-Med), where landscapes have a long history of human activities and practices, the spatial patterns of fire activity are strongly driven by human settlement patterns (Moreira et al., 2011), that change land cover (Martínez et al., 2009), supply the vast majority of ignitions (FAO, 2006), but also perform some form of suppression.

(Galiana-Martin et al., 2011) can be used below when talking about the wildland-urban interface.

Thanks, we modified the paragraph accordingly.

Lines 81-84 (reviewer 2): Can be merged into one sentence that covers all points.

Done

Line 83 (reviewer 2). furthermore instead of moreover

It is no longer used due to the last modification above.

Line 84 (reviewer 2). additionally instead of moreover

Thanks for suggestion. Done

Line85 (reviewer 2). Local singularities is an ambiguous term and more specific examples could be used.

Indeed. To remove ambiguities, we substituted this vague expression with examples.

Line 85 (reviewer 2): "Additionally, many factors, such as fire suppression or local singularities, are not easy to incorporate with measurable metrics to account for variance not explained."

Done

Line 103 (reviewer 2): I think there is a missing "but" after the citations. Also seen by reviewer.

Done, well spotted.

Line 108 (reviewer 2): "Here, we provide an update to our previous model by incorporating..."

We leave the original sentence, because due to some changes and shortenings in the introduction we never described the *Firelihood* before in this sentence, so it does not make sense to talk about "our previous model".

Line 128 (reviewer 2): A few sentences about the characteristics of the Matern covariance would be appreciated.

We added this short explanation (see lines 122-125):

"The Matérn covariance is a flexible and widely used covariance model in spatial statistics that includes the exponential covariance function as a special case, and it offers the advantage of numerical representations that remain manageable even with more than one thousand pixels as here (Krainski et al 2018)."

Line 135 (reviewer 2): "The impact of unaccounted factors on the estimation of effects..."

We changed the sentence according to your suggestion.

Line 138 (reviewer 2): Sentence a little wordy. Idea is there but needs to be written more directly

The sentence was shortened.

Line 141 (reviewer 2): No need to be harsh on the previous version

Corrected

Line 147 (reviewer 2): "We performed simulations with FL2 that allowed us to..."

Modified.

Line 169 (reviewer 2): Spatial resolution of SAFRAN, and if different than 2km, how was it aggregate or disaggregated.

We clarified the method as follows (see lines 158-160):

FWI was computed over the 2-km reference grid from meteorological variables extracted from the SAFRAN reanalysis (Vidal et al., 2010), using the cffdrs R package (Wang et al., 2017). For each 2-km pixel, we used the SAFRAN data corresponding to the 8-km pixel containing the center of the 2-km pixel of interest, i.e., we did not downscale the climatic data.

Line 175 (reviewer 2): Interpolated

We changed this to "we filled the missing values" to avoid confusion.

Line 176 (reviewer 2): table 1. I wonder the implications, if any, of the fuel rating being static. I know is not to the authors to update these values yearly, but if there are changes in LULC there must also be ones in fuel rating. In the same way, how to justify including both LULC type and fuel rating. Both these points need to be discussed here or later.

We agree that it would be better to have data over the temporal evolution of the fuel rating. Nonetheless, the nature of this grade would make it rather static over time, since it is partially based on geographical position (through the use of eco-regions) and type of forest and orientation, both of those characteristics are mostly stable over time, at least in the scale of time here accounted. In addition, this rating corresponds only to the forested areas, and even though the total surface changes, the rating stays equal for a same forest category.

The changes we observed in LULC are mostly between features inside a same category (e.g. different types of agriculture giving place to each other), and regarding forest cover (which is accounted for with variable “wildland area”), the CLC data is quite generalist (coniferous, broadleaved and mixed forests); given that, there are no big changes (e.g. big forest areas becoming agricultural crops). Therefore, it can be inferred that, as wildland area composition has been mostly stable over time, that fuel rating has also been stable.

Taking all of that into account, the fact that the fuel rating is static does not have a great impact on the modelling process. We only miss having strong data for agricultural abandonment rates, which is not easy to be found in databases as Copernicus' CLC, but this specific point should be the object of future research in the team.

The fact of including both LULC and a fuel type rating is justified since they have not the same source of data, neither the same spatial resolution nor specificity. This last one referring to the detail captured by each variable, whereas the CLC classes divide forest in 3 rough classes and include a class for shrublands, the fuel type rating has 42 different species or vegetation cover types crossed with 5 ecological zones. Nonetheless, it remains a spatially discontinuous (i.e., agricultural fuels are not considered) and expert-based information, so including CLC classes creates a better fill of the territory.

It may be worth to do some assessment of how the different types of LULC changed over time for each SER.

We included this assessment as Supplementary Materials S4

Lines 214-216 (reviewer 2): The reader would appreciate a refresher on how those work. Lower better? Higher better?

I added this precision in the text.

Lines 220-222 (reviewer 2): figure 1 does not match to what is being said here:

“These potential fire activities were averaged over time to draw a probabilistic occurrence map (Fig. 1B), which compares well with observations (Fig. 1A)” But figure 1 shows only a probabilistic map on the right, and on the left is an inset on where the study area is located. Also, can you expand a little more in explaining the figure.

Completely true. During the edition of the article, the Fig1 was transformed several times, and we did not add a figure with the model simulations afterwards. It is now added as Fig 2.

Line 236 (reviewer 2): How was the FWI made static? Daily average of first decade? Values of first year?

In fact, no single variable that is not already static was made static. The FWI of the first period was replicated in the second period, so the FWI value of August 1st 1993 will be affected to August 1st 2009, and so on, so it consisted in a translocation. We changed the word "fixing" by "reproducing" so it may avoid confusion towards interpreting that there is a conversion to static.

Line 248 (reviewer 2): Delete line.

Deleted

Lines 253-254 and 256 (reviewer 2): List them in correct order.

Done

Figure 2 (reviewer 2): X-axis would benefit from showing the units where possible, and the label of the Y-axis is confusing in what it means. A multiplier of 2 is two times more risk of fire, right?

Yes. This is what we call the multiplicative effect of the variable.

We have reinforced the caption for this figure.

Lines 275-276 (reviewer 2): The borders of the SERs can be imposed over the maps. Similarly, a hillshade with transparency would help identify trends associated to rugged terrain.

Done for the SERs.

Regarding the hillshade, the scale of these maps is quite small, and this type of layer would only add confusion over the colour reading. In additional materials there is already a map (Fig A1) with a hillshade and the SER’s boundaries.

All figures need some cleaning in terms of presentability. For example, consistency in size of window, in thickness of frame, etc.

We will take it into account. All graphical outputs are now systematized using R software and have the exact same sizes and thickness, the grid view of the multiple plots is also stable.

Lines 277-278 (reviewer 2): same as 253 and 254

Done

Figure 4 (reviewer 2): change the order of the bars so it is the same the legend. (Brown first, gray (?), then green)

Done

Line 311 (reviewer 2): Could this be because the fuel index is static?

The fact that the fire regime's evolution is not explained by the changes in LULC following our method is not a consequence of the fuel rating being static, since it is the only static variable in the LULC category, all other CLC classes are dynamic, therefore the static nature of the fuel rating may not be enough to produce such a contrasting result. Furthermore, as said in a previous answer, this fuel rating would not change as much, see also the answer to Line 176: table 1.

Lines 328-330 (reviewer 2): What is the unit for this figure? Similar to figure 1 (average number per year for respective decade)?

The anomaly here is the amount of change in fire numbers from the mean yearly fire number per pixel of the firsts period to the mean yearly fire number per pixel of the second period. We added a clarification in the figure's caption and legend.

The caption now reads: Fig. 6: "Comparison of simulations of fire activities between the past decade (1990-2003) and the recent decade (2009-2018) scenario and three alternative present scenarios in mean yearly fire numbers per pixel."

The borders of the SERs can be imposed over the maps. Similarly, a hillshade with transparency would help identify trends associated to rugged terrain.

Same as above.

Lines 332-342 (reviewer 2): Some sentences are redundant.

True, we merged the sentences that were redundant.

Lines 343-345 (reviewer 2): Fit better with the previous paragraph.

These lines were deleted, considering the comment from the reviewer, it is better not to create value of our model by comparing it to other methods, but to stand the value by itself.

Lines 346-352 (reviewer 2): Should be fixed to stand on its own as a paragraph.

It is now a paragraph.

For the discussion of LULC, I would suggest the writing is rearranged so that when one factor is discussed, both occurrence and size are mentioned.

Suggestion accepted, it is rearranged.

Line 361 (reviewer 2): "As observed on Costafreda et al"

Done

Line 365 (reviewer 2): "On the contrary..."

This connector was removed.

Lines 372-374 (reviewer 2): Were these factors also considered? Why not mentioned before?

Those factors were considered in an exploratory phase of this work, and due to their very low performance and significance we did not include them in the main work. Nevertheless, we considered it was both important and interesting to include this mention in the discussion to state that we did not ignore those variables.

Line375 (reviewer 2): "Although LULC variables..." and Line 377: This is a good point to start a new paragraph.

Because of some text reformatting, the paragraph separation was not evident in the new version of the manuscript. Line 375 is already a new paragraph.

Lines 393-396 (reviewer 2): Merge these into one sentence.

Done

Lines 406-411 (reviewer 2): Clarify this part.

Evin et al 2018, more that calling into question the current capabilities of the French system, it calls into question if the current policy of quick suppression is the most adequate. This quick suppression policy is most likely creating accumulation of fuel, which increases the risk of unmanageable fires.

Regardless of the main objective and methods of the concerned paper, the Evin and colleagues got to a clear conclusion, which is stated in their last paragraph. Extract from the conclusion of Evin et al. 2018:

> *"Extreme fire events (i.e., very large fires generating high human, economic, and ecological damages) are a growing issue in southern Europe and almost worldwide. Extreme fire events have a disproportionate impact on the media and they challenge the suppression-oriented policies because they question our ability to control or prevent them in the long term. In France, firefighting accounts for two-thirds of the total budget but it cannot suppress all large fires, as demonstrated notably in 2003, 2016 and 2017 (Chatry et al., 2010). Many large fires are erratic, fast growing, or convective (Lahaye et al., 2018) and cannot be controlled by firemen. They may belong to a new generation of fires promoted by global changes (Costa et al., 2011), which cause most of the accidents or fatalities for fire crews. <u>This study demonstrates that even if the fire policy established in 1994 in southern France is undoubtedly successful, changes for BA corresponding to large return periods appear barely significant.</u>"*

After questioning "if the current policy of quick suppression is the most adequate" in the cited article there is a direct announcement about the limitation on large fire extinction based on a short literature analysis. The current suppression policy, which may create the fuel built-up constraints, directly affects the fighting capabilities. Moreover, the last sentence of the citation segment (underlined) matches with our conclusion statement.

Chatry, C., Le Gallou, J., Le Quentrec, M., Lafitte, J., Laurens, D., Creuchet, D., and Grelu, J.: Rapport de la mission interministérielle "Changements climatiques et extension des zones sensibles aux feux de forêts", National Report on Climate Change and the Extension of Fire Prone Areas in France, Rapport Min. Alimentation Agriculture Pêche no. 1796, Paris, Tech. rep., 2010.

Costa, P., Castellnou, M., Larranaga, A., Miralles, M., and Kraus, D.: Prevention of Large Wildfires using the Fire Types Concept, Tech. rep., EU Fire Paradox Publication, Barcelona, Spain, 83 pp., 2011.

Lahaye, S., Curt, T., Fréjaville, T., Sharples, J., Paradis, L., and Hély, C.: What are the drivers of dangerous fires in Mediterranean France?, Int. J. Wildland Fire, 27, 155–163, https://doi.org/10.1071/WF17087, 2018.

Line 481 (reviewer 2): Can you provide a link for this.

This reference is deleted. See answer to Line 57 (reviewer 1).

Lines 567-571 (reviewer 2): Two citations merged into one

Well spotted, we have corrected this problem.

Missing citations for:

- Sutanto et al., 2021 → Added
- Barros and Ferreira 2009. → Citation deleted

Supplementary material and appendix.

All maps can benefit from superimposing the borders of the ERs and maybe a hillshade to identify rugged terrain.

We included the SER’s boundaries in thin black line. Regarding the hillshade, the scale of these maps is quite small, and this type of layer would only add confusion over the colour reading. In additional materials there is already a map (Fig A1) with a hillshade and the SER’s boundaries.