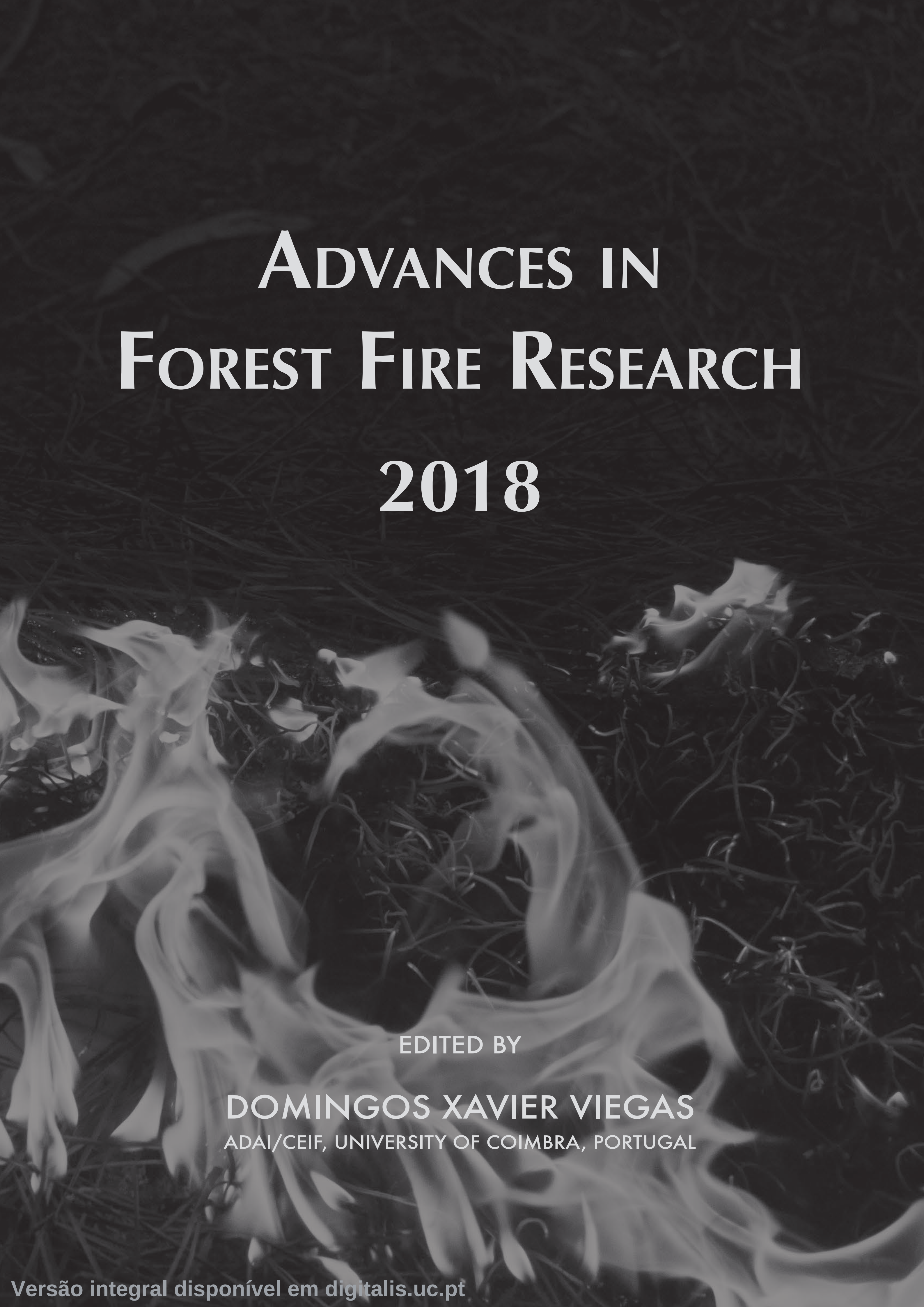

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Coimbra 2018

Composition
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thick and thermally thin prescriptions for fuels. This is possibly also caused by increased thermal conductivity in fuels with higher moisture content as described above.

Heat flux is significant as well. Comparing Figure 3a to 3b, we can see that Hausdorff distances between the mass loss rate curves of thermally thick and thermally thin prescriptions are uniformly greater with increased heat flux. This is likely influenced by the reduced disparity in ignition times mentioned above.

4.3. Fuel Composition

We find that the composition of a fuel is significantly influenced by whether the fuel is prescribed as thermally thick or thermally thin. These may be seen in Figure 1d and 1e. This finding makes sense given the different way that these fuels heat and thus pyrolyze. In particular, we see that moisture must be entirely purged from fuels treated as thermally thin before the wood may ignite.

The temperatures in the fuels also differ; we see that the fuel treated as thermally thin is heating more slowly than the other and that its temperature climb markedly slows as moisture is driven off. In the other fuel, temperature is more erratic due to its internal gradient and the process of driving off moisture is presumably less sudden since no such stall exists in the temperature data.

5. Conclusion

We established and validated a model for burning cylindrical fuels and recording their ignition times, mass loss rates, and material compositions. We numerically determined physical parameters for lodgepole pine fuel using experimental data. We conducted many experiments to establish the significance of fuel size, fuel moisture content, and fire intensity in the precision of thermally thin fuel prescriptions.

We found that thermally thin fuel prescriptions have insignificant effects on both ignition time delay and mass loss rate at fuel diameters around 1mm but that both are significantly effected at fuel diameters approaching 5mm. We found that lower heat flux and higher fuel moisture content reduce the significance of these differences to a limited extent but that fuel diameter remains the single most important determinant in whether a thermally thin fuel prescription is appropriate.

We conclude that thermally thin fuel prescriptions are entirely appropriate under the commonly accepted thickness of 1mm and suggest that, in cases where fuels are characterized by moderate to high moisture contents and are subjected to lower flux heat sources, they may be appropriate in slightly larger fuels. However, even with these conditions, they do suffer from loss of precision quite soon after. Researchers should carefully consider both their fuel and fire environment before using thermally thin fuel prescriptions.

6. Acknowledgements

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7. Appendices

7.1. Appendix A: Smallness of Thermally Thin fuels

Thermally thin objects are defined as being sufficiently small that no internal temperature gradient is formed under heating. Generally, it must be the case that the physical thickness, d, is less than the thermal penetration depth. For the temperature gradient to be small over region *d*, it must be the case that

$$Bi \equiv \frac{dh_c}{k} \ll \frac{h_c(T_s - T_o)}{\dot{q}''}$$

where *Bi* is the object's Biot number, h_c is the effective heat transfer coefficient, *k* is the thermal conductivity, T_s is the surface temperature of the object, T0 is the initial temperature of the object, and q̇'' is the heat flux (Quintiere, 2006). If these conditions are satisfied then the ignition time for a fuel prescribed as thermally thin should be very similar to that of a fuel prescribed as thermally thick.

7.2. Appendix B: Gpyro Formulations

Gpyro is used to numerically approximate material parameters described above in addition to parameters of a single step, heterogeneous reaction as:

$$\frac{\mathrm{d}\alpha}{\mathrm{d}t} = Z\exp\left(-\frac{E}{RT}\right)(1-\alpha)^n$$

Where α is the dimensionless conversion, *Z*- called *A* in the paper above- is the pre-exponential factor (s^{-1}), *E* is the activation energy (kJ/mol), *n* is the dimensionless reaction order (Lautenberger, 2009), *T* is temperature in °K, and *R* is the gas constant (8.314 J/mol).

Gpyro assumes that the density and thermal conductivity of each condensed phase species vary with temperature. In the case of conductivity:

$$k_i(T) = k_{s,i}(T) + k_{r,i}(T) = k_{0,i}\left(\frac{T}{T_r}\right)^{n_{k,i}} + \gamma_i \sigma T^3$$

where $k_{0,i}$ is the conductivity at reference temperature T_r, $n_{k,i}$ is the exponent that scales the conductivity, γ_i is the radiative portion of conductivity (for radiation crossing pores in the substrate) (Lautenberger, 2009), and σ is the Stefan-Boltzmann constant ($5.67*10^{-8}W*m^{-2}*K^{-4}$). Thus Gpyro establishes materials may change in conductivity with respect to temperature.

The parameters we numerically approximated are in Table 1.

Table 1 - Material and reaction parameters for lodgepole pine wood found through numerical approximation with Gpyro.

Name	**Unit**	**Value**
A (wood)	s^{-1}	2.45E+13
E (wood)	kJ/mol	178
Order	-	4.5
Rho initial (char)	kg/m^3	134
Conductivity initial (wood)	W/(m*K)	0.19
Conductivity initial (char)	W/(m*K)	0.095
Conductivity exp (wood)	-	0.038
Conductivity exp (char)	-	0.14
Specific Heat Cap. (wood)	J/(kg*K)	2845
Specific Heat Cap. (char)	J/(kg*K)	1734

8. References

Albini, F. and Reinhardt, E. (1995). Modeling Ignition and Burning Rate of Large Woody Natural Fuels. International Journal of Wildland Fire, 5(2):81-91

Lautenberger, C. and Fernandez-Pello, A.C. (2009). Generalized Pyrolysis Model for Combustible Solids. Fire Safety Journal, 44:819-839

Linn, R.R., Reisner, J. Colman J., Winterkamp J., 2002. "Studying wildfire behavior using FIRETEC." International Journal of Wildland Fire 11(3-4): 233-246.

McDermott, R., McGrattan, K., Floyd, D. (2017). FDS Road Map. https://github.com/firemodels/fds/wiki/FDS-Road-Map

McGrattan, K., McDermott, R., Weinschenk, C, and Forney, G. (2016). Sixth Edition Fire Dynamics Simulator Technical Reference Guide. NIST Special Publication 1018.

McGrattan, K., Hostikka, S., McDermott, R. (2017) Sixth Edition Fire Dynamics Simulator Technical Reference Guide Volume 1: Mathematical Model. NIST Special Publication 1018.

Mell W.E., Jenkins M.A., Gould J., Cheney P. (2007) A physics-based approach to modelling grassland fires. International Journal of Wildland Fire 16, 1-22.

Quintiere, J. (2006) Fundamentals of Fire Phenomena. John Wiley & Sons Ltd.

Ritchie, S., Steckler, K., Hamins, A., Cleary, T., Yang, G. and Kashiwagi, T. (1997). The Effect of Sample Size on the Heat Release Rate of Charring Materials. Fire Safety Science 5: 177-188.

Rockafeller, R. T. and Wets, R. JB (2005). Variational Analysis. Springer-Verlag. p. 117.

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Soil resilience under different scenarios of fire recurrence and severity in Pinus forest ecosystems affected by large wildfires

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Abstract

Fire is as a global phenomenon that represents one of the main disturbances in the Mediterranean *Pinus* forest ecosystem. It is also considered to be a soil forming factor and temporary modifier of soil properties. The degree of this impact depends on different factors such as pre-fire conditions, the type of soils affected, topographic and metereological characteristics and fire-regime attributes (e.g. fire size, recurrence, burn severity). In the last few decades, the fire regime is changing in some regions of the world including the Iberian Peninsula. This is the result of land abandonment, fire suppression policies and climate change. These factors generate a more favourable environment for the occurrence of large forest fires that may play a key role in affecting the natural rates and patterns of soils structure and functioning. As a consequence, both resiliency and sustainability of Mediterranean *Pinus* forest could be engaged. This survey is aimed at getting to know the effects of combined fire-regime attributes (recurrence and severity) on soil biochemical properties from a medium-term perspective (four years).

The study was conducted in the Sierra del Teleno mountain range (León province; NW Iberian Peninsula). The climate is Mediterranean with 2-3 months' dryness in summer. Soils are acidic (pH around 4.8) and mainly classified as Cambisol and Leptosol. A large wildfire occurred on August 19th 2012 affected an area of 119 km^2 (103 km^2 being occupied by *Pinus pinaster* Ait. forests). In this wildfire, a fire recurrence-severity map was elaborated by remote sensing methods, and validated using ground truth and with the information provided by the Regional Administration. We characterized fire recurrence throughout a 16-year period (1998-2014). Fire severity was measured by the dNBR (difference of the Normalized Burn Ratio) spectral index, and classified according to the ground reference values of the CBI (Composite Burn Index). We differentiated four scenarios of recurrence (low and high) and severity (low and high), and established a minimum of five 30m*30m field plots in each of the four recurrence-severity scenarios. In each field plot, we collected soil samples from a depth of 0-3 cm four years after the fire, and analysed the enzymatic activities β-glucosidase, urease, and acid-phosphatase and microbial biomass carbon.

Four years after the fire, it can be observed that fire-regime attributes have a great influence on the resilience of soil properties. In the scenario of low recurrence-high severity, which means the highest intensity fire, decreased phosphatase and urease activities and soil microbial biomass carbon. This scenario showed a slight resilience to β-glucosidase activity but marked depletion in the other soil properties. High recurrence scenarios favour the recovery of soil biochemical and microbial properties. Soil enzymatic activities and microbial biomass could be a proxy to identify the general state of soil health after large fires.

Keywords: enzymatic activities, medium-term, post-fire, recovery, soil microbial biomass, wildfires

1. Introduction

Fire is an important process which causes severe disturbances in many ecosystems, mainly in Mediterranean forest ecosystem. In this region, forests most affected by fire are pine ecosystems

(Moreira et al., 2008) with *Pinus pinaster* Ait. and *Pinus halepensis* Mill. as the dominant species. Fire impact on the ecosystem depends on different factors such as forest structure (Jain & Graham 2007; Shive et al., 2013), topographic and meteorological characteristics (Fang et al., 2018; Moreno & Chuvieco, 2016) and fire-regime attributes (Fernández et al., 2018).

In the last few decades, fire regime is changing in some regions of the world such as the Iberian Peninsula. This is the result of land abandonment, fire suppression policies and climate change (Moreno et al., 2014). These factors generate a more favourable environment for the increase in number and size of fires and thus in fire frequency (Guénon et al., 2013) and severity. As a consequence, natural rates and patterns of soil structure and functioning could be altered. Fire severity, defined as the loss of or change in biomass of the ecosystem caused by fire (Keeley, 2009), is used as an indicator of the fire's indirect impacts on the hydrological response of burned areas (Vieira et al., 2015). This is associated with negative effects mainly in soil physical properties such as water repellency and aggregate stability, and it is attributed to the changes in soil organic matter (Varela et al., 2015; Merino et al., 2018). Likewise, fire severity is a dominant factor in explaining changes in soil microbial communities and soil enzyme activity (Knelman et al., 2015), constraining the post-fire functioning of the ecosystem. On the other hand, fire recurrence continuously impoverishes soil especially in terms of organic matter and nutrients (Knicker, 2007) which would negatively affect to the recovery of microbial activities and increased the loss of ecosystem resilience in the long-term (Guénon et al., 2013).

On the other side, soil microbial biomass and enzyme activities are considered good indicators of soil quality and the impact of fire on soil (López-Poma & Bautista, 2014; Hinojosa et al., 2016). These properties are more sensitive to soil management practices or disturbances than chemical and physical ones (Dilly et al., 2018). The highest soil microbial content is found in natural ecosystems (woods and pastures) while this content decreases in managed ecosystems (crops and plantations) (Dilly et al., 2018) or in severely burned soils (Vega et al., 2013). The activity of soil enzyme is generally reduced immediately after fire (Vega et al., 2013; López-Poma & Bautista, 2014). The persistence of this impact can be ephemeral or persist several years according to the capacity of establishment of plant communities (Knelman et al., 2015) and the resilience of soil enzyme activity (López-Poma & Bautista, 2014).

Although different research has evaluated the effects of fire recurrence (Guénon et al., 2013) or fire severity (Vega et al., 2013) in both biochemical and microbiological soil properties, there are not studies analyzing the effects of the combination of fire regime attributes (recurrence and severity) in them. For this reason, the present survey is aimed at determining to know the role of combined fire-regime attributes (recurrence and severity) in soil resilience of biochemical and microbiological properties from a medium-term perspective (four years).

2. Material and methods

2.1. Study area

The study was conducted in the Sierra del Teleno mountain range (León province; NW Spain) The climate is Mediterranean temperate with an annual precipitation of 650-900 mm (Quintano et al., 2015) and an average temperature of around 11ºC. The area is characterised by a heterogeneous orography, with an elevation above sea level ranging from 850 to 2100 m. The lithologies are siliceous, and dominated by stones, silts, clays and conglomerates in the flat areas, and slate, sandstone, and quartzite in the mountainous ones (IGME, 1982). The soils are classified as Cambisol and Leptosol (Forteza et al., 1987) with a pH around 5, low soil organic carbon content (~2%), total nitrogen (~0.1%) and available phosphorous (< 5 mg kg^{-1}). The vegetation present before fire was covered mainly by *Pinus* *pinaster* Ait. with an understorey layer dominated by *Erica australis* L., *Pterospartum tridentatum* (L.) Willk., and *Halimium lasianthum* spp. *alyssoides* (Lam.) Greuter (Santalla et al., 2002)

Fires caused by dry spring-summer storms occur frequently in this forest ecosystem, but usually affect small areas. Nevertheless, a large fire occurred on 19th August 2012. This fire burned 119 km^2 being 103 km^2 being occupied by *P. pinaste*r forests, with a tree age of 35-95 years old. The weather conditions during the first day were 32ºC and 27% relative humidity. There was a very significant accumulated drought, with Haines index values of 6 (Quintano et al., 2015).

2.2. Field data collection and soil analysis

In this wildfire, a fire recurrence-severity map was elaborated by remote sensing methods, and validated using ground truth and with the information provided by the Regional Administration (Fernández-Manso et al., 2015) (Figure 1). To determine fire recurrence we considered the period 1998-2014 and classified as low (1 fire) and high (2 fires) recurrence. In order to characterise fire severity, we calculated the dNBR spectral index (Key, 2006) from the Landsat 7 ETM+ scenes of September 20th, 2011 (pre-fire situation) and September 6th, 2012 (post-fire). Four years after wildfire, a total of 44 field plots of 30 m x 30 m were established in four recurrence scenarios (low and high) and burn severity (low and high). The plots were randomly distributed in these scenarios with a minimum of 5 plots per recurrence-severity category: 10 plots for low recurrence-low severity; 10 plots for low recurrence-high severity; 10 plots for high recurrence-low severity and 14 plots for high recurrence-high severity.

To evaluate soil resilience, we collected two soil composite samples from each 30 x 30 m plot. Each soil sample was made up of four subsamples. The soil subsamples were collected along two 15 m perpendicular transects (N-W and S-W), after removing litter and plant debris from the surface, using an auger (5 cm diameter x 3 cm depth). This approach would allow the variability of the 30 x 30 plot to be captured. The soil samples were mixed, air-dried, sieved (< 2 mm) and stored at ambient temeperature for further analysis.

In these samples, we analysed three soil extracellular enzymatic activities corresponding to the biogeochemical cycles of C, N and P. Soil acid phosphatase and β-glucosidase activities were determined colorimetrically as the amount of p-nitrophenol (p-NP) produced after incubation of 0.5 and 1 g of soil (37ºC, 1 h) with p-nitrophenyl-phosphate and p-nitrophenyl-β-D-glucopyranoside substrates, respectively (Tabatabai and Bremner, 1969; Tabatabai, 1982). The p-NP formed was determined in a spectrophotometer at 400 nm (UV-1700 PharmaSpec, Shimadzu, Kyoto, Japan). Urease activity was determined following Kandeler & Gerber (1988) as the amount of N-NH4+ released from 1 g of soil after incubation (37ºC, 2 h) with urea substrate. The N-NH4+ released was measured colorimetrically at 690 nm. Two sample blanks for each soil sample were used.

Soil microbial biomass C content was determined by the fumigation-extraction method (Vance et al., 1987). This procedure is based on a Walkley-Black dichromate digestion to calculate the difference (E_C) in organic C between filtered extracts of chloroform fumigated (CHCl3, 24 h) and non-fumigated soil samples. Then, we used an extraction efficiency coefficient (k_{EC}) of 0.38 (Vance et al., 1987; Joergensen, 1996) to calculate the microbial biomass C following the formula: microbial biomass C = E_C/ k_{EC}.

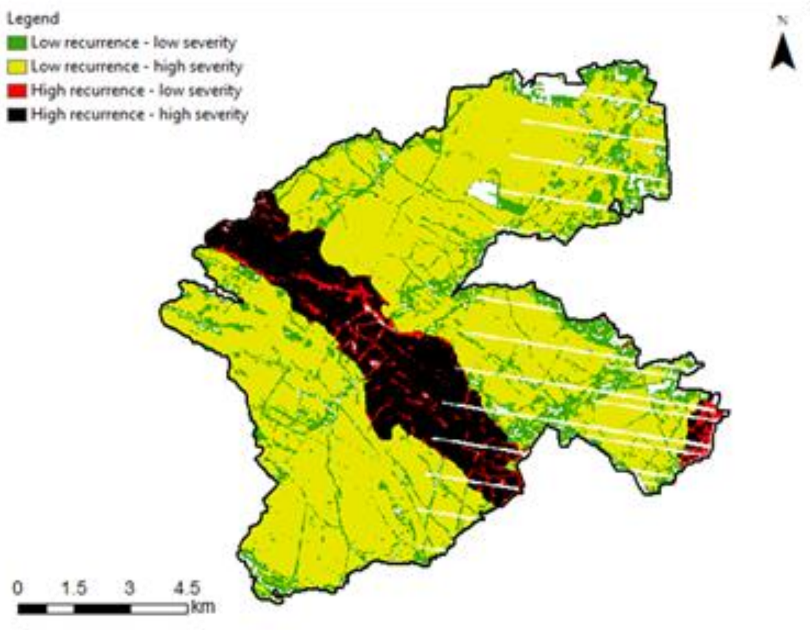

Figure 1 - Map of recurrence-burn severity levels in the study area

2.3. Resilience index

The soil enzymatic and microbial biomass resilience to different recurrence and severity scenarios was calculated using the resilience index developed by Banning & Murphy (2008):

$$Rx = -100 \left[\frac{Cx - Px}{Px}\right]$$

Where Rx is the reslience index; Cx is the value in the response variable in the low recurrence-low severity scenario, which was considered as a control value; Px is the value for the response variable in the other scenarios four years after fire. A Rx index value of zero indicates complete recovery at a given time x. Positive values indicate resilience of the response variable, while an Rx value of -100 indicates a further degradation of soil response variable.

2.4. Data analysis

In order to analyse the effects of recurrence-severity situations on soil biochemical and microbiological properties, we performed an ANOVA of the Generalised Linear Models (GLMs). GLMs were fitted using Gamma error distribution with the “log” link function. The goodness of fit of the models was assessed by visual analysis of homoscedasticity and normality of residuals. Differences in treatment levels were identified through a pairwise multiple comparison of means (Tukey HSD).

All data analyses were carried out with R software, version 3.4.0, using the “multcomp” package (Hothorn et al.,2008).

3. Results

Medium-term enzyme activities of β-glucosidase and acid phosphatase and urease showed a different pattern among the scenarios of recurrence and severity. β-glucosidase activity increased significantly (Table 1; Figure 2;) from the best scenario (low recurence-low severity) to the worst (high recurrence-high severity).

Table 1 - Results of the generalized linear models (GLMs) [‘Anova()’ outputs] showing the effects of the factor recurrence-severity (Low-Low, Low-High, High-Low and High-High) on each soil property (β-glucosidase, urease, phosphatase and microbial biomass C). Df are degrees of freedom. Significant P-values are in bold face.

Response variable	Model term	Df	Deviance	Residual deviance	F	*P*
β-glucosidase	Null			13.440		
	Recurrence-Severity	3	1.486	11.954	3.010	**0.035**
Urease	Null			32.648		
	Recurrence-Severity	3	5.270	27.378	5.864	**0.001**
Phosphatase	Null			37.344		
	Recurrence-Severity	3	6.315	31.029	4.655	**0.004**
Soil microbial C	Null			26.189		
	Recurrence-Severity	3	4.321	21.869	5.457	**0.002**

A different pattern was observed in urease activity with a significant decrease (Table 1; Figure 2) in the low recurrence-high severity scenario. In the case of acid phosphatase, significant differences were detected among high recurrence scenarios, and the low recurrence-high severity situation (Table 1; Figure 2) which presented the highest activity values.

Soil microbial carbon showed the lowest significant value in the low recurrence-high severity scenario (Figure 2; Table 1). We did not find significant differences amongst the remaining situations.

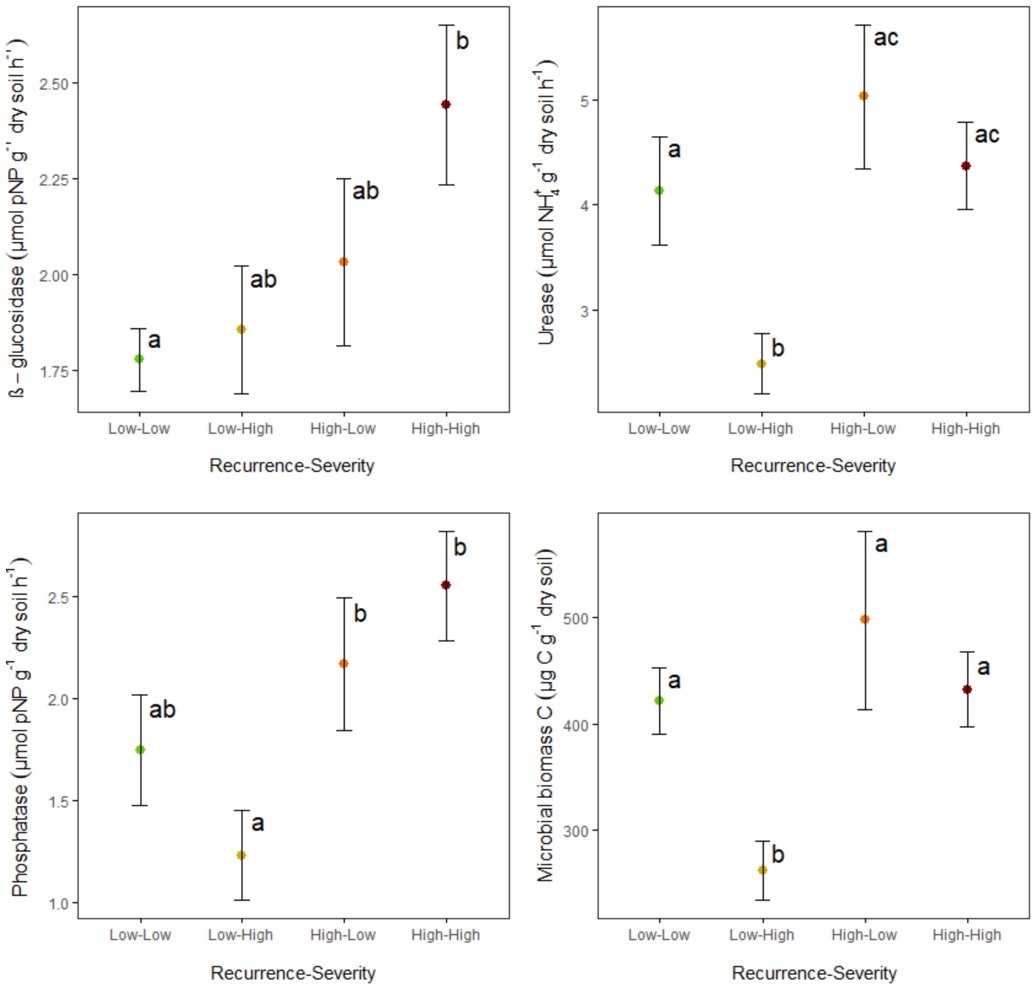

Figure 2 - Mean values ± standard error of soil properties (β-glucosidase, urease, phosphatase and microbial biomass C) in relation to the fire recurrence-severity (low recurrence-low severity, low recurrence-high severity, high recurrence-low severity and high recurrence-high severity). Different letters above the error bars (a, b, c) denote statistically significant differences between mean values ($p < 0.05$).

Soil enzymes showed different resilience capacity in relation different scenarios of recurrence-severity. β-glucosidase activity recovered well in all situations, reaching always higher values than low recurrence-low severity (Figure 2). Ureasa and acid phosphatase activities presented negative resilience values in low recurrence-high severity scenario (39% and 27% respectively) but good resilience in relation both high recurrence situations (Table 2). The same pattern was observed in soil microbial carbon, with an important degradation in low recurrence-high severity scenario (Table 2) but a good recovery in the other ones, mainly if the severity is low.

Table 2- Percentage of resilience (Rx) of soil enzymatic activities and microbial biomass in different scenarios of fire recurrence-severity scenarios (Low-High, High-Low and High-High)

Scenarios fire recurrence-severity scenarios	β-glucosidase	Urease	Phosphatase	Soil microbial C
Low-High	3.0 (13)	-39.4 (10)	-27.7 (18)	-37.7 (9)
High-Low	12.8 (12)	22.7 (23)	27.3 (27)	18.0 (28)
High-High	35.6 (13)	6.6 (12)	50.0 (18)	2.6 (10)

Values are means for each recurrence-severity scenario (n=10 for Low-High and High-Low and n=20 for High-High) with standard errors in parenthesis.

4. Discussion

This study examined the resilience of soil biochemical and microbiological properties to a combination of fire regime attributes: recurrence and severity. Our results demonstrated that the low recurrence-high severity scenario was the worst situation for the recovery of biochemical and microbiological properties throghout time. In this scenario (at least 14 years without fire), both the fuel load and the intensity and severity of fire. This could influence in the post-fire regeneration traits of plant species which modulate soil enzymatic activity recovery (López-Poma & Bautista, 2014). In this study area, we found that high severities negatively affected the cover of resprouter species but positively affected seeder species (Fernández-García et al., 2017). However, in the high recurrence scenarios the highest cover was due to resprouter shrubs, which rapidly increased their cover after fire. We found greater enzyme activity in those situations where resprouter species are dominant (high recurrence), because after a fire, the root system of the resprouter species is scarcely affected by fire, the microbiological rhyzosphere hotspots are more durable, and enzyme inputs to soils from root exudates are not interrupted (Mayor et al., 2016). Furthermore, the regeneration of resprouter species is very rapid and presents more nutrient demand and rhizosphere activity (López-Poma & Bautista, 2014).

On the other hand, enzyme activity showed a different response with regard to resilience. While β-glucosidase activity showed a positive recovery trend in all scenarios, acid phosphatase and urease showed a positive recovery under high recurrence scenarios but a degradation in low recurrence-high severity scenarios. Some authors have pointed out that the highest increase in β-glucosidase activity is related to greater plant density (Guénon et al., 2013), since there is an increase in enzyme substrate due to litter deposition and this produces an increase in the number of microorganisms (Mayor et al., 2016). The decrease in acid phosphatase and urease activity in the low recurrence-high severity scenario can be the result of of great availability of inorganic N and P, which often persist at medium-term after fire (Dzwonko et al., 2015), as in our study area (data unpublished). If the concentrations of nutrients is high, micro-organisms do not need to produce these extracellular enzymes (Pourreza et al., 2014), since they are substrate-dependent.

Although microbial biomass is markedly reduced by fire (Banning & Murphy, 2008), four years after it showed a good resilience except in the low recurrence-high severity scenario. This low resilience would be related with a decrease in the quality of soil organic matter, because of the emergence of new particulate C forms highly resistant to oxidation and biological degradation (González-Pérez et al., 2004) that act by limiting soil microbial recovery. However, frequent wildfires can enable the recovery of net nitrification and nitrate content, resulting in a recovery of C-substrate utilisation capabilities of microbial communities (Guénon et al., 2013) .Microbial biomass recovery was assessed by Prieto-Fernández et al. (1998) in a soil under *Pinus* spp. four years after fire, and was attributted to the addition of cellulose to the burnt soil favouring fungal mycelium development and the speed of plant recolonisation (Certini, 2005) and the litter layer.

The combination of fire regime attributes (recurrence and severity) had an important effect on soil resilience. High recurrence scenarios favour the recovery of soil biochemical and microbial properties, due to the rapid regeneration of resprouter species. Under these conditions urease activity and soil microbial biomass C do better if the severity is low, while an opposite pattern showed the other two enzyme activities. The low recurrence-high severity scenario negatively affects soil resilience, which results in a depletion of enzyme activities (except β-glucosidase) and soil microbial biomass C.

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6. References

Banning NC, Murphy DV (2008) Effect of heat-induced disturbance on microbial biomass and activity in forest soil and the relationship between disturbance effects and microbial community structure. *Applied Soil Ecology* **40,** 109-119.

Certini G (2005) Effects of fire on properties of forest soils: a review. *Oecologia* **143,** 1-10.

Dilly O, Pompili L, Benedetti A (2018) Soil micro-biological indicators separated land use practices in contrast to abiotic soil properties at the 50 km scale under summer warm Mediterranean climate in nirthern Italy. *Ecological Indicators* **84**, 298-303.

Dzwonko Z, Loster S, Gawronski S (2015) Impact of fire severity on soil properties and the development of tree and shrub species in a Scots pine moist forest site in southern Poland. *Forest Ecology and Management* **342,** 56-63.

Fang L, Yang J, White M, Liu Z (2015) Predicting potential fire severity using vegetation, topography and surface moisture availability in a Eurasian Boreal Forest Landscape. *Forests* **9,** 130.

Fernández-García V, Quintano C, Taboada A, Marcos E, Calvo L, Fernández-Manso A (2018) Remote sensing applied to the study of fire regime attributes and their influence on post-fire greenness recovery in pine ecosystems. *Remote Sensing* **10**, 733.

Fernández-García V, Baeza J, Santana VM, Tárrega R, Valbuena L, Taboada A, Luis-Calabuig E, Fernández-Guisuraga JM, Suárez-Seoane S, Marcos E, Calvo L (2017) ¿Son diferentes los rasgos biológicos de las plantas en relación con la severidad de incendios en pinares propensos al fuego?. Actas del 7º Congreso Forestal Español, Plasencia. .pp. 1-10.

Fernández-Manso F, Fernández-García V, Quintano C, Marcos E, Calvo L (2015) Cartografía de recurrencia-severidad en grandes incendios forestales utilizando técnicas de teledetección. Actas del XVI Congreso de la AET. Sevilla, Spain.

is complex since the degree of conversion varies within the material and its thermal parameters must be known or estimated.

There are many different approaches to modeling the thermal degradation of wood. The first approach considers that the wood decomposes in tars, chars and gases. The tars decompose then into gas and char according to two parallel reactions (referred to as secondary reactions) (Thurner and Mann 1981, Di Blasi 1993, Shafizadeh and Chin 1977). Another type of kinetic approach considers that wood consists of three biopolymers, which are hemicellulose, cellulose and lignin. Each of these polymers then decompose independently (Di Blasi 2008, Di Blasi 1993) and can be studied separately. Other approaches for the thermal degradation of wood have considered successive stages of degradation of virtual compounds. For example, Fateh et al. (Fateh *et al*. 2013) used a six steps successive kinetic mechanism to describe the thermal degradation of plywood whereas Benkorichi et al. (Benkorichi *et al*. 2017) tested a model with seven steps to represent the thermal degradation of pine needles. Finally, the last approach considers the reduction of the degree of polymerization during the degradation by introducing an “active” material. This approach was used by Shafizadeh and Bradbury (Shafizadeh and Bradbury 1979) to represent the cellulose decomposition.

In this context, we proposed to evaluate three kinetic mechanisms describing the thermal decomposition of two woods: oak and eucalyptus under oxidizing atmosphere. For this, the study was conducted at matter and material scales by using thermally thin wood plates. This kind of plates has two advantages. First of all, small pieces of this plate can be used in TGA experiments. Unlike the use of powder, the structure of the sample is not altered while avoiding temperature gradients in the material. For experiments at the material scale, using thermally thin plate avoids the temperature gradients inside the plate and the necessity of determining the thermal parameters of the material. Therefore, these experimental conditions allow to focus only on the kinetics of wood decomposition. The work presented hereafter is divided into three parts. The first section describes the experimental devices used for the experiments at both scales and the tested kinetic mechanisms. The second section presents the evaluation of the kinetic mechanisms on TGA experiments. In the last section, we present the results of the tests at material scale with regards to the kinetic mechanism, that showed the performance at matter scale.

2. Materials and Methods

2.1. Experimental devices

The multi-scale experiments were performed with two species of woods: oak (*Quercus alba*) and eucalyptus (*Eucalyptus globulus*) by using wooden sheets of 0.6 mm depth thick. For all experiments, the wood plates were oven-dried at 60°C during 24 hours to remove the moisture.

Experiments at matter scale were conducted with a PerkinElmer Pyris 1 thermogravimetric analyzer under oxidizing atmosphere. The samples were cut from the thermal thin plate in discs of 5 mm diameter corresponding to an initial dry mass of 4.4 mg (± 0.6 mg) and 6.2 mg (± 0.5 mg) for oak and eucalyptus, respectively. The discs were placed in a 33 µl open platinum crucible. The samples were heated up to 650°C with five heating rates varying between 2 and 30 °C/min. To focus on the thermal degradation, we only considered the mass loss recorded between 150 and 650°C in order to avoid the effects of the dehydration of free water. The sample temperature was controlled by a thermocouple and did not exhibit any systematic deviation from preset linear temperature programs. Three repetitions were done for each kind of wood and each heating rate.

The experiments at material scale were carried out with a cone calorimeter (Babrauskas *et al*. 1992). Pieces of $100 \times 100 \times 0.6$ mm^3 were cut in the wooden sheets for samples. Then, they were placed on ceramic wool in a sample holder mesh basket of 10×10 cm^2 made of stainless steel (Tihay-Felicelli *et al*. 2016). They were oven dried at 60°C during 24 hours before each experiment. The sample holder was then positioned on a load cell over an insulating ceramic. Before each set of experiments, the load cell was calibrated using standard weighs. Its precision was 0.1 g and the sampling frequency was equal to 1 Hz. Two radiant heat fluxes (20 and 25 kW/m²) were imposed at the top of the plates. They were chosen in order to obtain fast heating rates while avoiding the flaming. The level of radiant heat flux was checked by using a flux meter before each experiment. The smoke extraction was set up with an exhaust fan at a flow rate of 24 l/s. The plate temperature was recorded by two K-type thermocouples with a sampling frequency of 25 Hz. They were placed on the back surface of the plate in order to avoid the radiation sent by the cone calorimeter. The first thermocouple was located at the center of the plate. The other one was placed at 1 cm from the edge of the plate. As the plates were assumed thermally thin, we considered that the temperature of the plate could be represented by the average of the values recorded with both thermocouples. The mass loss and temperature measurements were performed separately because thermocouples induce pressure on the load cell, which alter the initial mass and the mass loss recorded. At least three replicates were done for each experimental setup.

2.2. Kinetic mechanisms

Based on the literature (Di Blasi 1993, Shafizadeh and Chin 1977, Shafizadeh and Bradbury 1979), three kinetic mechanisms with four stages were developed for the thermal decomposition of dry wood. For all kinetic mechanisms, the degree of conversion α is defined as follows:

$$\alpha = \frac{m-m_0}{m_f-m_0} \tag{1}$$

Where m is the mass. The subscripts 0 and f correspond to the initial time and the final time respectively.

The first mechanism is based on an approach by constituents (Di Blasi 2008, Di Blasi 1993, Grønli et al. 2002) (called constituent approach). The dry wood (DW) is assumed to consist of hemicellulose, cellulose and lignin:

$$DW = \ p_1\,Hemicellulose + p_2\,Cellulose + p_3\,Lignin \tag{2a}$$

$$Hemicellulose \rightarrow \nu_1 Char + (1-\nu_1)Gas \tag{2b}$$

$$Cellulose \rightarrow \nu_2 Char + (1-\nu_2)Gas \tag{2c}$$

$$Lignin \rightarrow \nu_3 Char + (1-\nu_3)Gas \tag{2d}$$

$$Char \rightarrow \nu_4 Ash + (1-\nu_4)Gas \tag{2e}$$

Where p_1 , p_2 and p_3 represent the mass proportion of each component in the wood composition.

The reaction rates of these steps are defined as follows:

$$\dot{\omega}_i = (1-\alpha_i)^{n_i}.A_i.exp\left(-\frac{Ea_i}{R.T}\right) \qquad \text{for } 1 \le \text{i} \le 3 \tag{3a}$$

$$\dot{\omega}_4 = (p_1\alpha_1 + p_2\alpha_2 + p_3\alpha_3 - \alpha_4)^{n_4}.A_4.exp\left(-\frac{Ea_4}{R.T}\right) \tag{3b}$$

The total conversion rate was then obtained with the following equation:

$$\frac{d\alpha}{dt} = (1-\nu_1)\dot{\omega}_1 + (1-\nu_2)\,\dot{\omega}_2 + (1-\nu_3)\,\dot{\omega}_3 + (1-\nu_4)(p_1\nu_1 + p_2\nu_2 + p_3\nu_3)\,\dot{\omega}_4 \tag{4}$$

The second mechanism (called lumped approach) (Shafizadeh and Chin 1977, Fateh *et al*. 2013, Benkorichi *et al*. 2017) considers the following steps where the dry wood is degrading in other forms of wood before leading to char and ashes:

$$DW \rightarrow \nu_1 DW_1 + (1-\nu_1)Gas \tag{5a}$$

$$DW_1 \rightarrow \nu_2 DW_2 + (1-\nu_2)Gas \tag{5b}$$

$$DW_2 \rightarrow \nu_3 Char + (1-\nu_3)Gas \tag{5c}$$

$$Char \rightarrow \nu_4 Ash + (1-\nu_4)Gas \tag{5d}$$

For this mechanism, the reaction rates of these steps are defined as follows:

$$\dot{\omega}_1 = \frac{d\alpha_1}{dt} = (1-\alpha_1)^{n_1} A_1 \exp\left(-\frac{E_{a_1}}{RT}\right) \tag{6a}$$

$$\dot{\omega}_i = \frac{d\alpha_i}{dt} = (\alpha_{i-1}-\alpha_i)^{n_i} A_i \exp\left(-\frac{E_{a_i}}{RT}\right) \qquad \text{for } 2 \le i \le 4 \tag{6b}$$

The total conversion rate was then obtained as follows:

$$\frac{d\alpha}{dt} = (1-\nu_1)\dot{\omega}_1 + (1-\nu_2)\nu_1\dot{\omega}_2 + (1-\nu_3)\nu_1\nu_2\dot{\omega}_3 + (1-\nu_4)\nu_1\nu_2\nu_3\dot{\omega}_4 \tag{7}$$

In the third mechanism (called active mechanism) (Shafizadeh and Bradbury 1979, Bradbury *et al*. 2003), the degradation of dry wood includes a first step that accounts for the formation of “active wood”, which corresponds to a reduction in degree of polymerization. Then the degradation of active wood leads to gas, tar and char. Then tars and chars undergo respectively devolatilization and oxidation:

$$DW \rightarrow \nu_1 Active\ wood + (1-\nu_1)Gas \tag{8a}$$

$$Active\ wood \rightarrow \nu_2 Char + \nu_3 Tar + (1-\nu_2)Gas \tag{8b}$$

$$Tar \rightarrow Gas \tag{8c}$$

$$Char \rightarrow \nu_4 Ash + (1-\nu_4)Gas \tag{8d}$$

The reaction rates of this mechanism are calculated with the following relationships:

$$\dot{\omega}_1 = \frac{d\alpha_1}{dt} = (1-\alpha_1)^{n_1} A_1 \exp\left(-\frac{E_{a_1}}{RT}\right) \tag{9a}$$

$$\dot{\omega}_2 = \frac{d\alpha_2}{dt} = (\alpha_1-\alpha_2)^{n_2} A_2 \exp\left(-\frac{E_{a_2}}{RT}\right) \tag{9b}$$

$$\dot{\omega}_3 = \frac{d\alpha_3}{dt} = (\alpha_2-\alpha_3)^{n_3} A_3 \exp\left(-\frac{E_{a_3}}{RT}\right) \tag{9c}$$

$$\dot{\omega}_4 = \frac{d\alpha_4}{dt} = (\alpha_2-\alpha_4)^{n_4} A_4 \exp\left(-\frac{E_{a_4}}{RT}\right) \tag{9d}$$

The total conversion rate was then obtained thanks to the following equation:

$$\frac{d\alpha}{dt} = (1-\nu_1)\dot{\omega}_1 + (1-\nu_2-\nu_3)\nu_1\dot{\omega}_2 + \nu_1\nu_3\dot{\omega}_3 + (1-\nu_4)\nu_1\nu_2\dot{\omega}_4 \tag{10}$$

The kinetic parameters (E_a, A, n and ν) of each reaction as well as the constituent proportions were determined by using the genetic algorithms method. To determine the best set of kinetic parameter, the following objective function was minimized:

$$\mathcal{F} = \sum_{i=1}^{N}\left(\alpha_i^{exp}-\alpha_i^{cal}\right)^2 + \left(\frac{d\alpha}{dt}\Big]_i^{exp} - \frac{d\alpha}{dt}\Big]_i^{cal}\right)^2 \tag{11}$$

Where the exponents exp and cal represent the experimental and calculated values and N the number of points of the experiments.

The performance of each set of parameters was calculated for each evaluated curve as:

$$Fit = \sqrt{\frac{\mathcal{F}}{N}} \tag{12}$$

3. Thermal degradation at matter scale

3.1. Experimental results

Figure 1 presents the evolution of the non-dimensional mass loss and the rate of change of mass (which corresponds to the mass loss rate divided by the initial mass) obtained by TGA for oak and eucalyptus with a heating rate of 10 °C/min representative of the other conditions. For both woods, the thermal degradation takes place in four steps, which is consistent with the kinetic mechanisms tested. The mass loss rate exhibits a first peak around 300°C followed by the most significant mass loss rate peak at about 350°C. A shoulder is then visible around 400°C. Finally, the last peak takes place after 500°C that corresponds to the char oxidation. For both woods, the non-dimensional mass loss and the rate of change of mass follow the same trends even if some differences can be observed. The different steps appear at the same temperature for both woods excepted for the char oxidation, which appears between 450°C and 500°C for oak and beyond 550°C for eucalyptus. This phenomenon comes from a longer duration of the shoulder observed for eucalyptus. By comparing the intensity of the rates of change of mass, we observe that the main difference occurs for the first step. The peak is nearly two times higher for oak than eucalyptus. According to literature (Grønli *et al*. 2002), this first reaction corresponds mainly to hemicellulose degradation, the second one to cellulose degradation whereas the shoulder is characteristic of lignin degradation. According to literature (da Silva *et al*. 2010, Pettersen 1984), the percentages of hemicellulose, cellulose and lignin correspond to 28%, 40% and 25% respectively for oak and to 17%, 46% and 33% for eucalyptus. Therefore, oak has more hemicellulose and less lignin than eucalyptus. This is in agreement with a higher rate of change of the first reaction for oak and with a longer duration of the shoulder for eucalyptus.

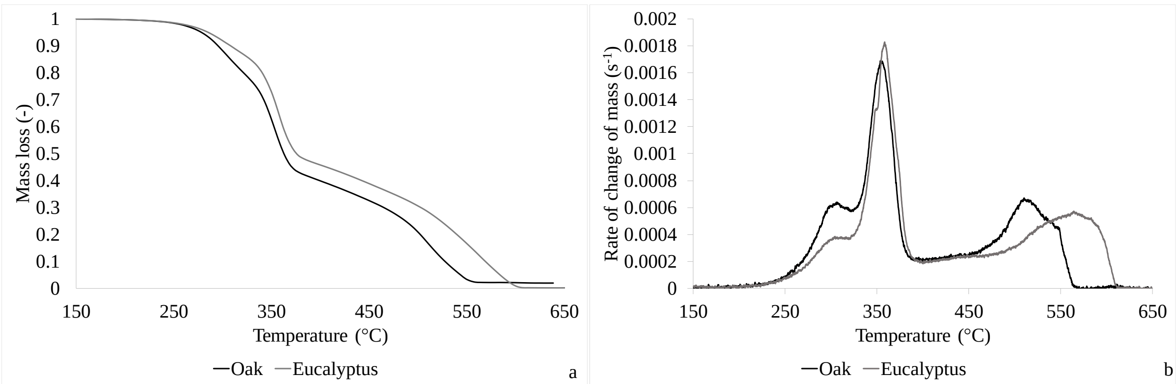

Figure 1- Evolution of a) the mass loss and b) the rate of change of mass at a heating rate of 10 °C/min for oak and eucalyptus.

3.2. Mass loss simulation

The experimental curves obtained by TGA with the five heating rates were used to calculate the set of parameters used in the three kinetic mechanisms. Table 1, 2 and 3 present the values obtained for both woods. Considering the constituent approach, the activation energies for the degradation of hemicellulose, cellulose and lignin are around 160 kJ/mol, 190 kJ/mol and 169 kJ/mol for both woods. These values are in agreement with literature (Chen *et al*. 2015, Arseneau 1971). Regarding the lumped approach, the activation energies of the three first reactions are between 161.1 and 188.9 kJ/mol for oak and between 143.4 and 300.0 kJ/mol for eucalyptus. These values are higher than those obtained for pine needles in the literature (Benkorichi *et al*. 2017, Fateh *et al*. 2017). For the active approach, the activation energies of the three first reactions are between 109 and 197 kJ/mol and vary little for both woods. These values are higher than those found in the literature for cellulose (around 58 kJ/mol) (Bradbury *et al*. 2003). Concerning the char oxidation, there is little difference between the mechanisms. For the constituent and the lumped approaches, the activation energies are around 120 kJ/mol whereas for the active mechanism the value is around 130 kJ/mol for both woods. These values are close of the results of Cancellieri et al. (Cancellieri *et al*. 2013) but are much lower than those found by Conesa et al. (Conesa *et al*. 1995), for which the activation energies for char oxidation are between 179 and 219 kJ/mol. To compare the accuracy of the three mechanisms on the prediction of TGA curves, the mean value of the performance parameter calculated for the five heating rates (equation 12) was indicated in tables 1 to 3. In addition, figure 2 shows the experimental and predicted mass losses for a heating rate of 10 °C/min for both woods. All kinetic mechanisms provide good predictions of the mass loss. The mass evolutions calculated with the three mechanisms by using the optimized model parameters are indeed very close to the experiments. The performance factor varies indeed between 0.96×10^{-2} and 1.84×10^{-2}. The best agreement was obtained with the lumped approach for both woods.

Table 1 - Kinetic parameters for oak and eucalyptus with constituent approach.

Species	Reactions	n_i	$\ln(A_i)$ (s^{-1})	E_{ai} (kJ/mol)	ν_i	p_i	Mean Fit (-)
Oak	1	1.43	29.87	160.99	0.41	0.26	1.37×10^{-2}
	2	1.44	31.91	189.83	0.14	0.55	
	3	1.46	21.82	168.39	0.16	0.19	
	4	0.52	12.06	117.24	0.00	-	
Eucalyptus	1	1.59	29.76	159.34	0.56	0.22	1.84×10^{-2}
	2	1.47	31.93	191.06	0.18	0.55	
	3	1.74	22.13	169.32	0.35	0.23	
	4	0.50	11.63	121.45	0.00	-	

Table 2 - Kinetic parameters for oak and eucalyptus with the lumped approach.

Species	Reactions	n_i	$\ln(A_i)$ (s^{-1})	E_{ai} (kJ/mol)	ν_i	Mean Fit (-)
Oak	1	1.17	29.72	161.06	0.84	1.27×10^{-2}
	2	1.32	31.67	188.92	0.45	
	3	1.89	22.29	164.89	0.66	
	4	0.59	12.41	118.05	0.00	
Eucalyptus	1	1.40	25.97	143.42	0.88	0.96×10^{-2}
	2	1.64	39.22	227.15	0.52	
	3	3.00	46.22	300.00	0.72	
	4	0.71	11.57	119.12	0.00	

Table 4 - Kinetic parameters for oak and eucalyptus with the active approach.

Species	Reactions	n_i	$\ln(A_i)$ (s^{-1})	E_{ai} (kJ/mol)	ν_i	Mean Fit (-)
Oak	1	0.63	18.19	109.14	0.86	1.78×10^{-2}
	2	0.82	24.73	188.81	0.31	
	3	2.62	33.41	195.54	0.64	
	4	0.50	14.58	128.63	0.04	
Eucalyptus	1	0.65	19.06	111.51	0.92	1.20×10^{-2}
	2	1.02	25.66	187.64	0.37	
	3	1.82	33.48	197.68	0.52	
	4	0.85	13.95	134.45	0.00	

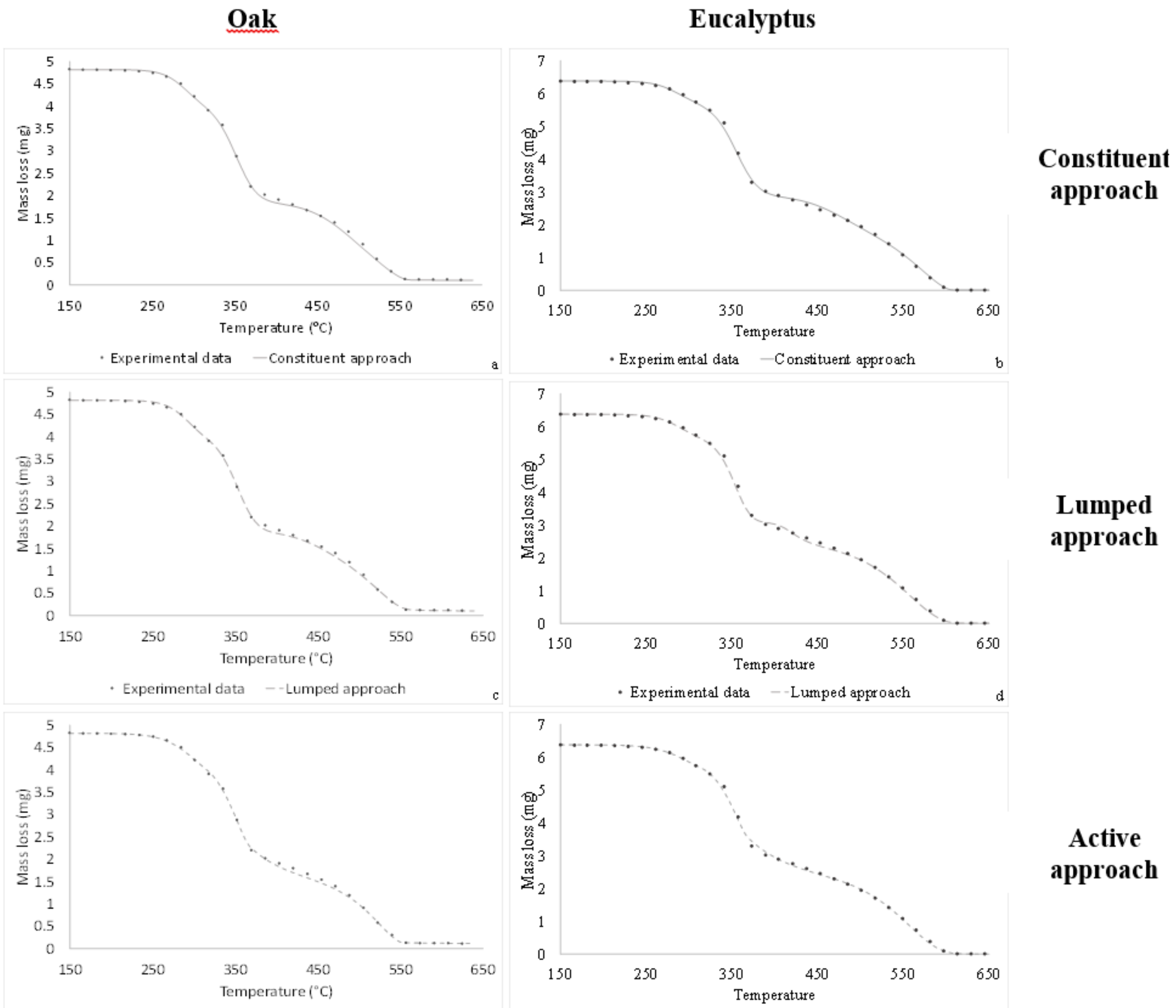

Figure 2 - Comparison of the experimental and predicted mass losses for a heating rate of 10 °C/min for oak and eucalyptus: a and b) with constituent approach c and d) with lumped approach e and f) with active approach.

4. Thermal degradation at material scale

4.1. Experimental results

Figure 3 presents the time evolution of the temperature and the mass loss for the plates of oak and eucalyptus exposed to a radiant heat flux of 25 kW/m². For both woods, the mean temperature recorded at the back surface of the plate follows the same trend. After the shutter opening, the plate temperature increases quasi-linearly until reaching a temperature of 615°C. For oak, the temperature increases slightly faster than that for eucalyptus. The plates begin to degrade around 20 s (Fig. 3.b) which corresponds to a temperature of 230°C for oak and 180°C for eucalyptus. The mass loss is maximal near 60 s corresponding to a temperature around 400°C. These results are consistent with the TGA experiments where the maximum mass loss rate occurs around 350°C (Fig. 1). Although no flaming occurred during the experiments, both plates lost their entire initial mass at the end of the tests. These observations are consistent with TGA experiments (Fig. 1.a).

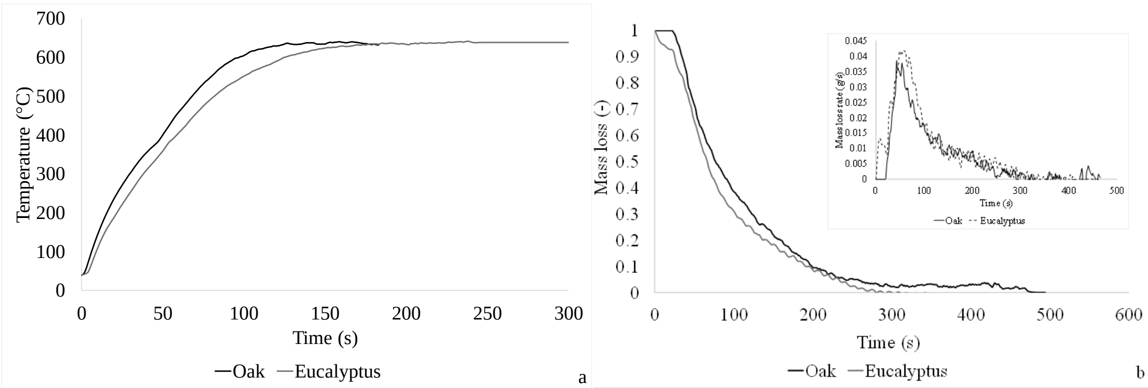

Figure 3 - Time evolution of a) the mean temperature at the back surface and b) the mass loss and mass loss rate – for a radiant heat flux of 25 kW/m².

4.2. Test of the lumped approach

The experiments performed with the cone calorimeter were used to test the lumped approach, corresponding to the kinetic mechanism with the best performance at matter scale. Figure 4 shows the experimental and predicted mass loss obtained with the lumped approach for oak and eucalyptus for two levels of radiant heat flux (20 and 25 kW/m²). Two behaviors can be observed. For oak and eucalyptus with a radiant heat flux of 20 kW/m², until 180 s (400°C), the mass loss calculated with the lumped approach shows a good agreement with the experimental data. Above this threshold the model prediction overestimates the mass loss. It suggests that the model for char oxidation needs to be modified at this scale. For a radiant heat flux of 25 kW/m², a delay occurs for both woods between the simulated and experimental mass after 30 s (corresponding to a temperature of 200°C) leading to a bad mass loss prediction. To understand why the kinetic mechanism provides a good prediction at 20 kW/m² but a bad one at 25 kW/m², the temperatures of the lower and upper faces were measured (Fig. 5). Although the wood plates are very thin (0.6 mm), at 25 kW/m², there is a temperature gradient inside the plate. The upper surface of the wood has indeed a higher temperature. The assumption of a thermally thin material is no more valid for this radiant heat flux. This temperature difference has strong consequences. The upper surface will indeed begin to degrade before the lower face. Taking the back face temperature to perform the mass loss prediction introduces therefore a delay. Consequently, the temperature gradient within the plate has to be taken into account to model the degradation at material scale for such radiant heat fluxes.

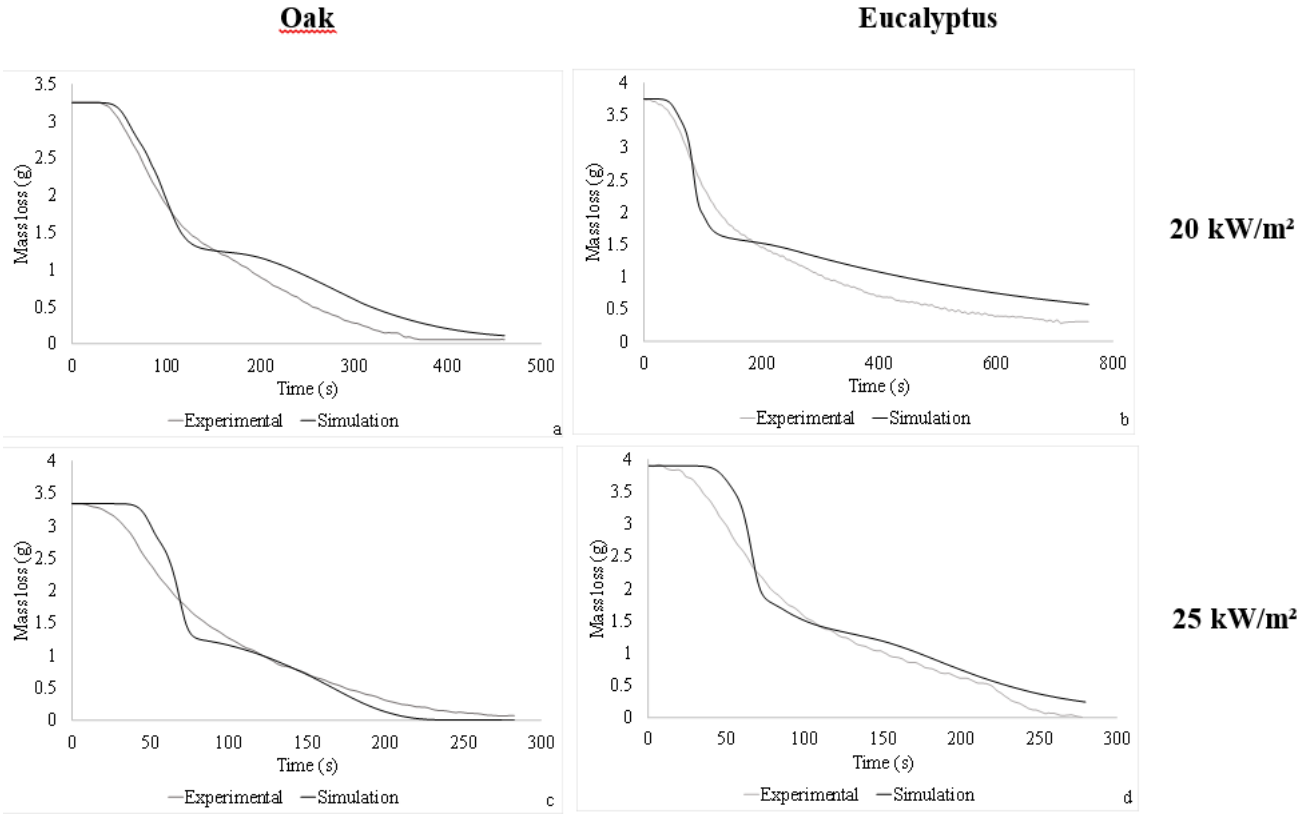

Figure 4 - Comparison between experimental and predicted mass loss for: a) oak at 20 kW/m² b) eucalyptus at 20 kW/m² c) oak at 25 kW/m² and d) eucalyptus at 25 kW/m²

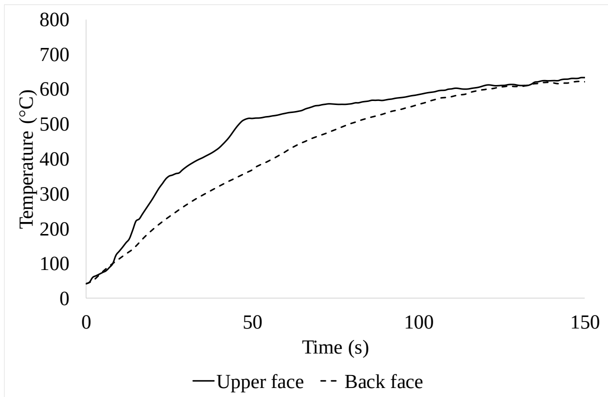

Figure 5 - Temperature recorded on the back and upper faces of the oak plate exposed to a radiant heat flux of 25 kW/m²

5. Conclusion

In this article, three kinetic mechanisms were tested in order to model the thermal degradation of wood plates at matter and material scales. To focus only{Bibliography} on kinetics, thermally thin wood plates were used for the experiments at the different scales. The main results can be summarized as follows:

- The three models predict efficiently the thermal decomposition at matter scale for the different heating rates investigated.

- The use of thermally thin wood plates allows testing kinetic mechanisms at 20 kW/m² without the knowledge of the thermal properties of the wood. A good concordance was observed between the experimental and predicted results except for char oxidation. For a radiant heat flux of 25 kW/m², the use of plates with 0.6 mm depth did not allow a thermal equilibrium within the depth of the sample. For such radiant heat flux, the temperature gradient within the plate has to be taken into account to test the kinetic mechanisms of degradation at material scale.

6. References

Arseneau DF (1971) Competitive Reactions in the Thermal Decomposition of Cellulose, *Canadian Journal of Chemistry* **49** (1971), 632–638. doi:10.1139/v71-101.

Babrauskas V, Twilley WH, Janssens M, Yusa S (1992) A cone calorimeter for controlled-atmosphere studies. *Fire Materials* **16**, 37–43. doi:10.1002/fam.810160106.

Benkorichi S, Fateh T, Richard F, Consalvi JL, Nadjai A (2017) Investigation of thermal degradation of pine needles using multi-step reaction mechanisms, *Fire Safety Journal* **91**, 811–819. doi:10.1016/j.firesaf.2017.03.058.

Bradbury AGW, Sakai Y, Shafizadeh F (2003) A kinetic model for pyrolysis of cellulose. *Journal of Applied Polymer Science* **23**, 3271–3280. doi:10.1002/app.1979.070231112.

Cancellieri D, Innocenti E, Leroy-Cancellieri V (2013) WinGPYRO: A software platform for kinetic study of forest fuels. *Fire Safety Journal* **58**, 103–111. doi:10.1016/j.firesaf.2013.01.005

Chen Z, Hu M, Zhu X, Guo D, Liu S, Hu Z, Xiao B, Wang J, Laghari M (2015) Characteristics and kinetic study on pyrolysis of five lignocellulosic biomass via thermogravimetric analysis. *Bioresource Technology* **192**, 441–450. doi:10.1016/j.biortech.2015.05.062.

Conesa JA, Caballero J, Marcilla A, Font R (1995) Analysis of different kinetic models in the dynamic pyrolysis of cellulose. *Thermochimica Acta* **254**, 175-192. doi:10.1016/0040-6031(94)02102-T

Da Silva MR, Machado G de O, Deiner J, Calil Junior C (2010) Permeability measurements of brazilian Eucalyptus. *Materials Ressource* **13**, 281–286. doi:10.1590/S1516-14392010000300002.

Di Blasi C (1993) Modeling and simulation of combustion processes of charring and non-charring solid fuels. *Progress in Energy and Combustion Science* **19**, 71–104. doi:10.1016/0360-1285(93)90022-7.

Di Blasi C (2008) Modeling chemical and physical processes of wood and biomass pyrolysis. *Progress in Energy and Combustion Science* **34**, 47–90. doi:10.1016/j.pecs.2006.12.001.

Fateh T, Rogaume T, Luche J, Richard F, Jabouille F (2013) Kinetic and mechanism of the thermal degradation of a plywood by using thermogravimetry and Fourier-transformed infrared spectroscopy analysis in nitrogen and air atmosphere. *Fire Safety Journal* **58**, 25–37.

Fateh T, Richard F, Zaida J, Rogaume T, Joseph P (2017) Multi-scale experimental investigations of the thermal degradation of pine needles. *Fire and Materials* **41**, 654–674. doi:10.1002/fam.2407.

Grønli MG, Várhegyi G, Di Blasi (2002) Thermogravimetric analysis and devolatilization kinetics of wood. *Industry and Engineering Chemistry Research* **41**, 4201–4208.

Leroy V, Cancellieri D, Leoni E (2006) Thermal degradation of ligno-cellulosic fuels: DSC and TGA studies. *Thermochimica Acta* **451**, 131–138. doi:10.1016/j.tca.2006.09.017.

Mell W, Maranghides A, McDermott R, Manzello SL (2009) Numerical simulation and experiments of burning douglas fir trees. *Combustion and Flame* **156**, 2023–2041.

Pettersen RC (1984) The Chemical Composition of Wood. *The Chemistry of Solid Wood,* 57–126.

Poletto M, Zattera AJ, Santana RMC (2012) Thermal decomposition of wood: Kinetics and degradation mechanisms. *Bioresource Technology* **126**, 7–12.

Shafizadeh F, Chin PPS (1977) Thermal Deterioration of Wood. *Wood Technology: Chemical Aspects*, 57–81. doi:10.1021/bk-1977-0043.ch005.

Shafizadeh F, Bradbury AGW (1979) Thermal degradation of cellulose in air and nitrogen at low temperatures. *Journal of Applied Polymer Science* **23**, 1431–1442.

Tihay-Felicelli V, Santoni PA, Barboni T, Leonelli L (2016) Autoignition of Dead Shrub Twigs: Influence of Diameter on Ignition. *Fire Technology Journal* **52**, 897–929. doi:10.1007/s10694-015-0514-x.

Thurner F, Mann U (1981) Kinetic investigation of wood pyrolysis. *Industry Engineering Chemical Process Development* **20**, 482–488. doi:10.1021/i200014a015.

species were split into two groups of different flammability (Fig. 1). Agreeing with previous works (Trabaud, 2000; Dimitrakopoulos, 2001), *P. halepensis* belonged to the most flammable species, along with two terpeneless species *Cotoneaster franchetti* and *Elaeagnus ebbingei* (mostly due to high ignition frequency and long flaming duration) while the four others were ranked as not very flammable (mostly due to long time-to-ignition).

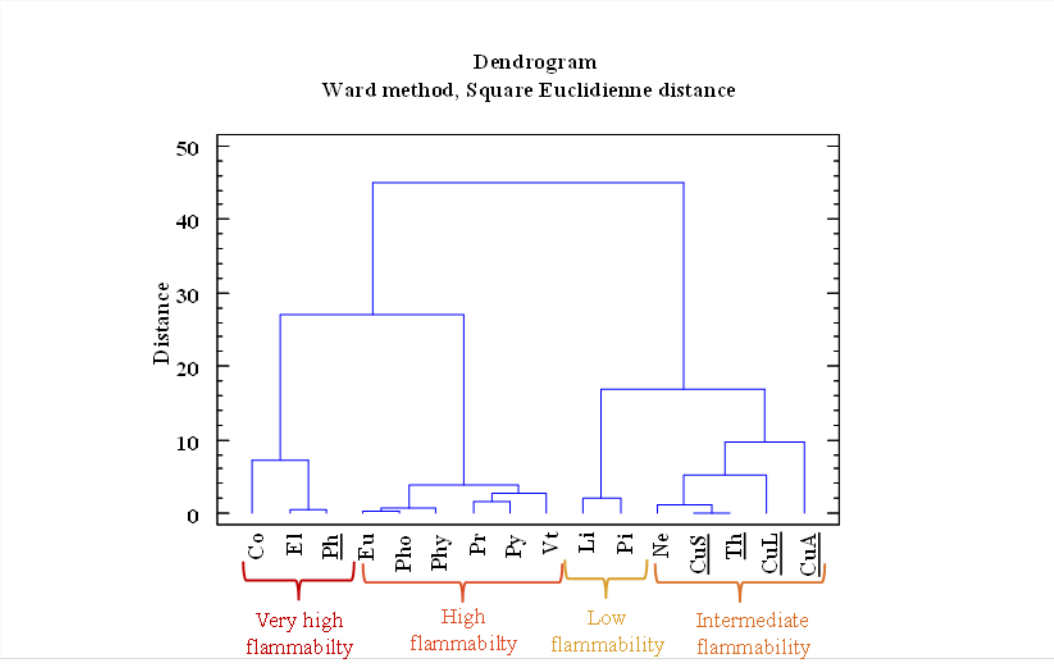

***Figure 1** - Ranking of the 16 ornamental species from the most flammable to the least flammable species according to leaf flammability (underlined: species containing terpenes, Co: Cotoneaster franchetii, CuA: Cupressus arizonica, CuL: Cupressocyparis leylandii, CuS: Cupressus sempervirens, El: Elaeagnus ebbingei , Eu: Euonymus japonicus, Li: Ligustrum japonicum, Ne: Nerium oleander, Ph: Pinus halepensis, Pho: Photinia fraseri, Phy: Phyllostachys sp., Pi: Pittosporum tobira, Pr: Prunus laurocerasus, Py: Pyracantha coccinea, Th: Thuja occidentalis, Vt: Viburnum tinus).*

Along with the high sesquiterpene, *P. halepensis*' leaves also presented high SVR as well as low density and FMC in contrast to less flammable species containing terpenes whose leaves were thicker and denser and presented higher monoterpene and diterpene contents. The least flammable species (*Pittosporum tobira* and *Ligustrum japonicum*) did not contain terpenes and presented low ignitability and sustainability, mostly due to higher leaf moisture content along with high density and low SVR (Fig. 2).

Except for ignition frequency significantly predicted by diterpene content (negative effect, logistic regression, $p=0.002$), the flammability of species containing terpenes was mostly driven by sesquiterpene content (positive effect), combined to leaf density (negative effect) regarding flaming duration (multiple regression, $p=0.002$) and to FMC and thickness (positive effect) regarding time-to-ignition (multiple regression, $p<0.0001$). *P. halepensis* was the species best characterizing these relationships, this species presenting the highest amount of sesquiterpenes (mostly due to caryophyllene: 0.905 mg g^{-1} which was the most concentrated molecule among the entire set of compounds identified). When this latter species was removed from the analyses, sesquiterpene content was not a significant driver of flammability anymore, replaced by diterpene content (negative effect on TTI). Several other fire-prone species also presented high sesquiterpene contents, such as the Australian *Malaleuca quinquenervia* (Ireland *et al.* 2002) or several Mediterranean species of *Cistus* (especially caryophyllene for *C. monspeliensis;* Llusià and Peñuelas 1998) whose germination is triggered by fire. In the current study, monoterpene content was not a significant driver of flammability contrary to the results of Pausas *et al.* (2016) obtained on *Rosmarinus officinalis*. This latter species produces monoterpenes (some presenting high contents such as camphrene) differing from those found in the species we studied; this could be an explaination to this difference. Other works showed, however, that monoterpenes were poorly related to flammability or were overridden by FMC (Alessio *et al*. 2008a, 2008b).

For the terpeneless species, leaf thickness best predicted flammability (negative effect) combined to surface-to-volume ratio and FMC (negative effect) regarding flaming duration, to leaf density (positive effect) regarding time-to-ignition, and to leaf density and surface-to-volume ratio (negative effect) regarding ignition frequency (for all relationships, $p<0.0001$). When all the species were pooled in the multiple regression analyses, sesquiterpene content was still one of the best predictors of time-to-ignition and flaming duration, highlighting the strong impact of *Pinus halepensis* in the relationships.

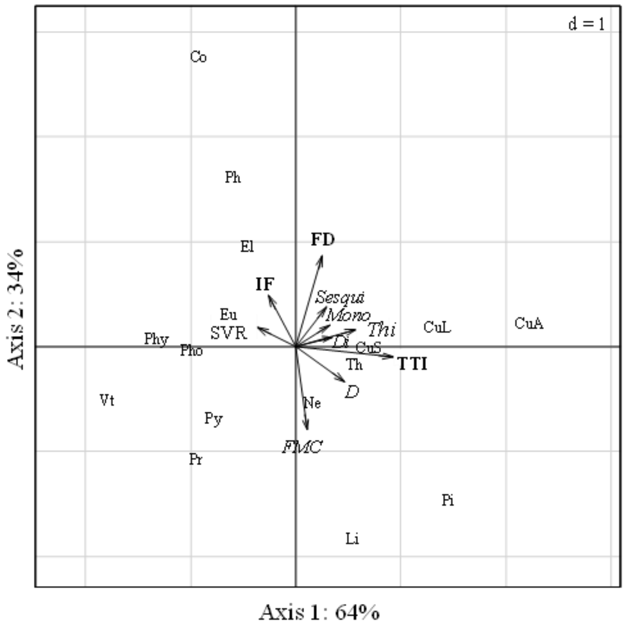

Figure 2 - Co-inertia analysis highlighting the relationships between the leaf characteristics of the 16 ornamental species and their flammability variables. The two first components together explain 98% of the total variance (D: leaf density, SVR: surface-to-volume ratio, FMC: fuel moisture content, Thi: leaf thickness, Mono: monoterpene content, Sesqui: sesquiterpene content, Di: diterpene content, Co: Cotoneaster franchetii, CuA: Cupressus arizonica, CuL: Cupressocyparis leylandii, CuS: Cupressus sempervirens, El: Elaeagnus ebbingei , Eu: Euonymus japonicus, Li: ligustrum japonicum, Ne: Nerium oleander, Ph: Pinus halepensis, Pho: Photinia fraseri, Phy: Phyllostachys sp., Pi: Pittosporum tobira, Pr: Prunus laurocerasus, Py: Pyracantha coccinea, Th: Thuja occidentalis, Vt: Viburnum tinus).

4. Conclusion

The present work showed that the sesquiterpene content (especially the caryophyllene content) was one of the strongest predictor of flammability highlighting that species containing high amount of this terpene (e.g. *P. halepensis*) would be among the most flammable and thus should be avoided in WUI, along with terpeneless species with low FMC and leaf density (e.g. *C. franchetti* and *E. ebbingei* contrary to *P. tobira* and *L. japonicum*). The other species that presented high monoterpene and diterpene contents were also characterized by thicker and denser leaves that were less flammable. However, the amount of dead fuel trapped in the canopy of some of these species (e.g. *Cupressus sempervirens*) strongly increases their flammability (Ganteaume *et al*. 2013a) and should also be avoided close to housing, especially when they form horizontal fuel continuity (as in ornamental hedge) that can easily propagate the fire. Moreover, as flammability can differ between live leaf and dead surface fuel within a given species (Ganteaume 2018), it will be important to also assess the role of terpene contents on litter flammability.

5. References

Alessio GA, Peñuelas J, Llusià J, Ogaya R, Estiarte M, De Lillis M (2008a) Influence of water and terpenes on flammability in some dominant Mediterranean species. *Int. J. Wildland Fire* **17**, 274-286.

Alessio GA, Penuelas J, De Lillis M, Llusia J (2008b) Implications of foliar terpene content and hydration on leaf flammability of Quercus ilex and Pinus halepensis. *Plant Biology* **10**, 123-128.

Dimitrakopoulos A (2001) A statistical classification of Mediterranean species based on their flammability components. *Int. J. Wildland Fire* **10**, 113-118.

Ganteaume A (2018) Does plant flammability differ between leaf and litter bad scale? Role of fuel characteristics and consequences for flammability assessment. *Int. J. Wildland Fire*. https://doi.org/10.1071/WF17001.

Ganteaume A, Jappiot M, Lampin C, Guijarro M, Hernando C (2013a) Flammability of some ornamental species in wildland–urban interfaces in southeastern France: laboratory assessment at particle level. *Environ manag*. **52**, 467-480.

Ganteaume A, Jappiot M, Lampin C (2013b) Assessing the flammability of surface fuels beneath ornamental vegetation in wildland–urban interfaces in Provence (southeastern France). *Int. J. Wildland Fire* **22**, 333-342.

Grootemaat S, Wright IJ, Bodegom PM, Cornelissen JH, Cornwell WK (2015) Burn or rot: leaf traits explain why flammability and decomposability are decoupled across species. *Functional Ecology* **29**, 1486-1497.

Grootemaat S, Wright IJ, van Bodegom PM, Cornelissen JH. 2017. Scaling up flammability from individual leaves to fuel beds. *Oikos* **126**, 1428-1438.

Ireland B, Hibbert D, Goldsack R, Doran J, Brophy J (2002) Chemical variation in the leaf essential oil of Melaleuca quinquenervia (Cav.) ST Blake. *Biochemical Systematics and Ecology* **30**, 457-470.

Llusià J, Peñuelas J (1998) Changes in terpene content and emission in potted Mediterranean woody plants under severe drought. *Canadian Journal of Botany* **76**, 1366-1373.

Ormeno E, Cespedes B, Sanchez IA, Velasco-García A, Moreno JM, Fernandez C, Baldy V. (2009) The relationship between terpenes and flammability of leaf litter. *For. Ecol. Manag*. **257**, 471-482.

Pausas JG, Alessio GA, Moreira B, Segarra-Moragues JG (2016) Secondary compounds enhance flammability in a Mediterranean plant. *Oecol.* **180**,103–110.

Trabaud L (2000) Post-fire regeneration of *Pinus halepensis* forests in the West Mediterranean. Ecology, Biogeography and Management of *Pinus halepensis* and *P. brutia* Forest Ecosystems in the Mediterranean Basin. Backhuys Publishers, Leiden, The Netherlands, 257-268.

Yani A, Pauly G, Faye M, Salin F, Gleizes M. (1993) The effect of a long-term water stress on the metabolism and emission of terpenes of the foliage of Cupressus sempervirens. *Plant, Cell & Environment* **16**, 975-981.

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The large fire of Pedrógão Grande (Portugal) and its impact on structures

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Abstract

The fire complex that began on 17/6/2017, in Central Portugal, will be for always remembered, not only because of the extensive burned area, but mainly because it caused 65 deaths, more than 200 injured and destroyed hundreds of structures, making it one of the most serious accidents in the country, and one of the worst in Europe. The Forest Fire Research Centre of ADAI (University of Coimbra, PT) performed a detailed analysis and report on this fire complex focused on aspects related to the fire spread and behaviour, the mortal accidents and the fire impact on local communities. The work presented here is related to the latter, i.e., the destruction of property. The greatest impact was observed in the municipalities of Pedrógão Grande, Castanheira de Pera and Figueiró dos Vinhos, where the deaths occurred and where most of the damaged structures were located. This component of structural damage was the subject of an intensive fieldwork, during which we inventoried several aspects related to fire behavior, the structures and their surroundings. During the field work, 1043 structures damaged by fire were identified. They are mostly support structures, such as barracks or storage (38.6%), but there is a considerable number of damaged dwellings, either permanent (13.3%) or temporary (11.9%). One of the most important aspects of the study relates to the type and location of structural ignition. More than 60% of the structures have been ignited due to the deposition of incandescent particles (firebrands) in different weak points. Likewise, more than 60% of these ignitions occurred on the roofs, mainly because of the vulnerability associated to the structures and materials supporting them. Another relevant factor is the observation of the advanced age of most buildings affected (over 30 years), which may indicate less resistance to the passage of a fire. Nevertheless, and for the Portuguese reality, we can say that buildings are generally safe during the passage of a fire, if themselves and their surroundings are kept in good conditions. The fact that there are people inside can be essential in their defense and resistance to the passage of fire.

This paper presents the main results of the assessment of the fire impact on structures, part of a larger work on the Fire Complex of Pedrógão Grande and neighboring municipalities.

Keywords: WUI; impact on structures; large fire

1. Introduction

The analysis of the impact of a fire on a given community has inherent the concept of Wildland Urban Interface (WUI), or simply interface. WUI can be simply defined as the space where structures and vegetation coexist in a fire prone environment (BRP, 2008). We must also add the human component (Ribeiro, 2016), because it is mainly people who are affected. This impact can be hard to evaluate, given the difficulty in obtaining measurable data that allows the establishment of gradations of social, economic or even emotional and familiar impact. From a purely structural impact perspective, it becomes more feasible to gather a set of parameters that allow us to estimate how the fire has impacted the community affected.

The way in which the structures in the WUI are damaged by wildfires has received special attention all over the world (e.g. Cohen, 2003; Cohen & Saveland, 1997; Gollner *et al.*, 2015; Graham *et al.*, 2012; Westhaver, 2016) and efforts have been made by the scientific community, but also the operational and technical ones, in order to understand the ignition mechanisms of the structures and the weaknesses they present to the passage of a wildfire. For instance, Blanchi *et al.*, (2012) carried out an historical analysis on the impact of fire on people and structures across Australia between 1901 and 2011. During this work specific databases were created to allow data harmonization and collection. Inspired by this report, we designed customized geodatabases to allow us the systematic collection of data related to the impacts of the wildfire complex of Pedrógão Grande and neighbouring municipalities, namely on personal accidents resulting in deaths, and on structures damaged. The geodatabases where simple but were designed to collect the maximum amount of detail in the field work, considering the time available to execute the field campaign.

After the extensive field campaign, a detailed analysis of all the collected data was performed, and published in the respective fire report (Viegas et al., 2017). We present here what we believe to be some of the most important results obtained.

2. Methods

The analysis of the impact of fire on structures was based on field verification of all buildings damaged by fire, regardless of their use or type. For this purpose, a geodatabase and a geospatial form of simple interpretation and completion were constructed. The database comprised 3 sections: i) description of the structures, for example the type of structure, age, fuel management in the surroundings, condition before and after the fire and usage, among others. The second section was related to describing how the fire affected the structure, namely, the ignition point and the way the structure ignited. The last section was related to fire details (time of arrival, impact on electricity, water, communications) and human behavior (escape/stay and defend, injuries, deaths).

Given the size of the affected area and the time available to carry out the survey and analysis, visiting the entire burned area searching for affected structures would be extremelly hard to accomplish. Therefore, the initial planning comprised the search for initial data sources related to the location of damaged structures. For this, we asked the affected municipalities for information on the structures impacted by the fire in each of them. From the municipalities of Castanheira de Pera, Figueiró dos Vinhos, Penela and Sertã we obtained georeferenced data of the structures that they identified as having been damaged in some way by the fire. Together with Pedrogão Grande, these were the municipalities selected to carry out the fieldwork and the respective analysis. To our knowledge, these surveys were carried out in all municipalities in order to allow applications for reconstruction or rehabilitation support. Later we obtained this data also from the municipality of Góis (27 houses damaged by fire), Pampilhosa da Serra (8 dwellings and 20 agricultural wharehouses) and Alvaiázere (10 structures but only a secondary housing), but they were not included in the fieldwork and therefore the analysis. From the municipality of Pedrógão Grande we were not able to obtain this information. However, at the beginning of this work we were invited to join an initiative of *Esri Portugal - Sistemas e Informação Geográfica, SA* (the official distributor of the North American Esri - Environmental Systems Research Institute, world leader in the technology of Geographic Information Systems), to support the decision in the wildfire of Pedrógão. This initiative was titled "FireHub 2017" and consisted in the creation of a collaborative open data platform (available in June 2017 at http://arcg.is/2rMwc0B). Using this platform, we had access to a set of georeferenced points representing structures allegedly damaged by fire, especially in the municipality of Pedrógão Grande, but with some cases in Castanheira de Pera and Penela. These points were not validated by any entity, so we proceeded with some care to include them in our work.

The impact of the fire was especially noted in the municipalities of Pedrógão Grande, Figueiró dos Vinhos and Castanheira de Pera, so the analysis presented focuses mainly on that region. We also decided to include the neighboring municipalities of Penela and Sertã, since they have suffered considerable damage, albeit in a smaller area. In the municipalities of Góis and Pampilhosa da Serra the impact of the fire was lower. It was not possible to extend the study to those two municipalities, due to difficulties related to the execution time of this work.

We were able to gather a substantial set of georeferenced points, which allowed us to schedule the field visits. These points, for a total of 704, represented, for the most part, permanent housings. During the fieldwork, 289 of these points proved to be false. In some cases, there were not even structures in the place indicated by the points, in others the structures had not been damaged by the fire. As we said before, we were interested in all structures damaged by the fire, not only the housings, so during the field work we inventoried another 684 points that were not listed initially. In total, 1388 points were visited, of which 1099 points were initially considered valid. Figure 1 shows the location of all points visited (valid and false) as well as the points not visited, referring to Góis (27), Pampilhosa da Serra (28) and Alvaiázere (10).

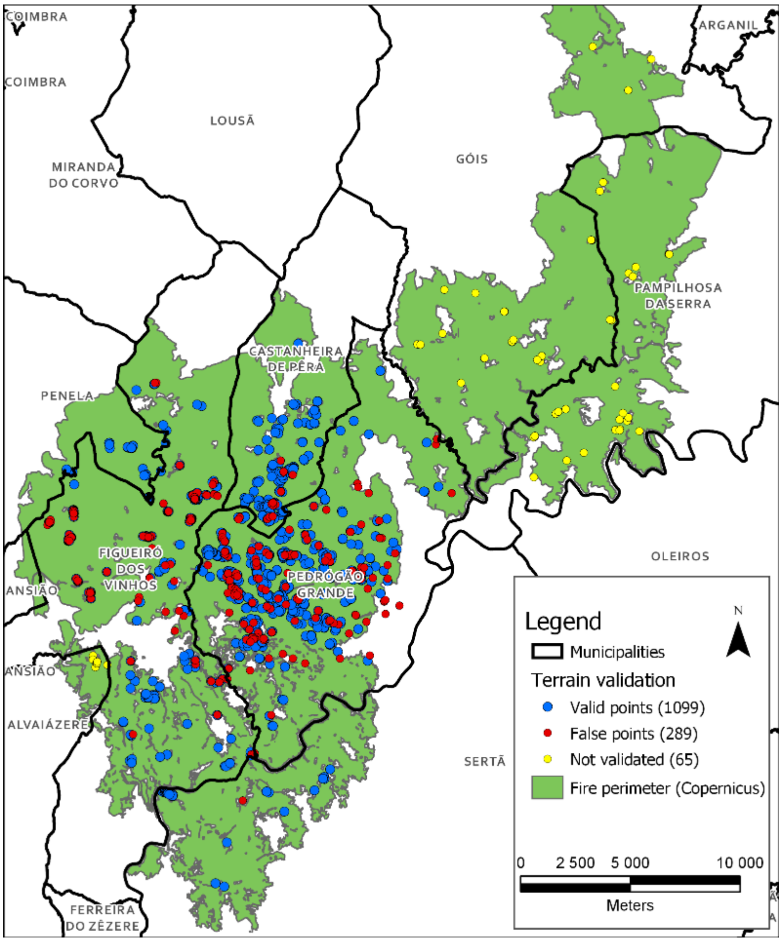

Figure 1 - Location of all points visited (blue and red) and not visited (yellow)

During the field work we encountered several structures in ruins that were already in that state before the fire. Although we started registering them, the number we encountered was so large (and the data gathered not that meaningful) that we decided to leave them out of the analysis. In total, discounting these structures, we finished with 1043 valid points that fulfilled the requirements for analysis.

3. Results and discussion

In total, 1043 points (representing affected structures) were considered valid for analysis, from approximately 1400 points visited. The data collected in the field work was treated and analyzed in ArcMap and IBM SPSS Software. Figure 2 shows a density map of damaged structures, or "heatmap". It can be clearly seen the area where the impact was greatest. This area, comprised of five municipalities, also coincides with the region of more extreme fire behavior and to where the 65 victims were found.

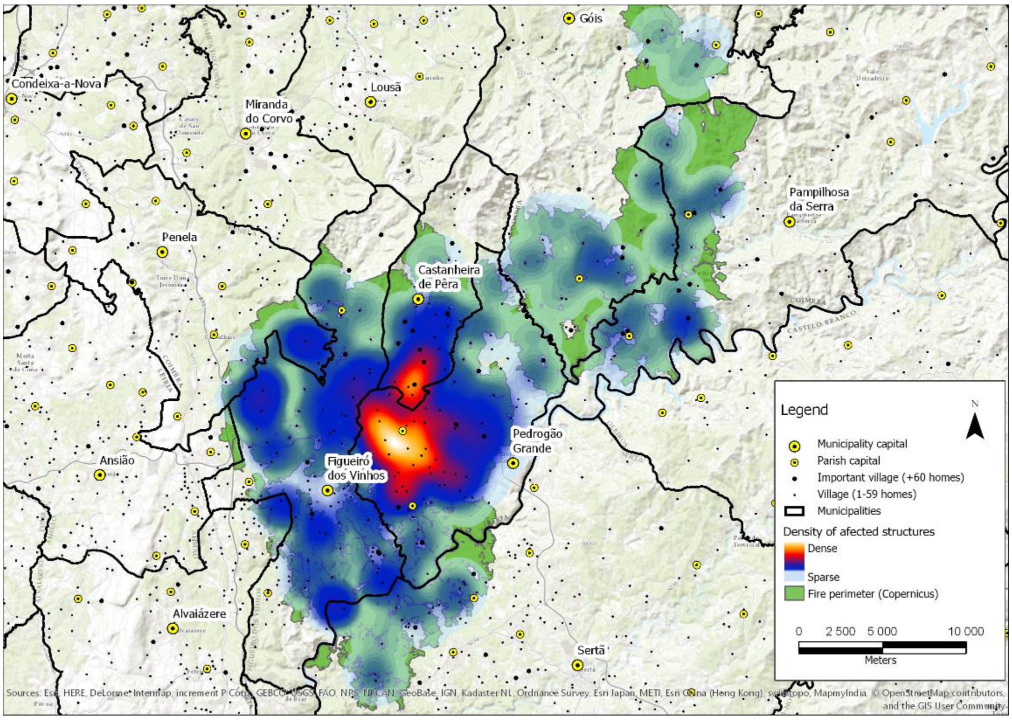

Figure 2 - Heatmap of damaged structures

This was the region chosen for the fieldwork and subsequent analysis. The data collected was treated and analyzed in ArcMap and IBM SPSS Software. Results were grouped in three categories: i) relating to the structure, ii) relating to the surroundings of the structure and iii) relating to the arrival and impact of fire. In the next tables (Tables 1 through 3) we present some of the most relevant results from each of these categories. A most complete set of results can be consulted in Viegas et al., 2017.

Table 1 - Results from the field work related to i) the structure

Variable		**Structure condition after the fire**				**Total**
		Slightly damaged	**Moderately damaged**	**Highly damaged**	**Totally destroyed**	
Type of structure	Permanent housing	35	17	46	41	139
	Secondary housing	19	9	46	50	124
	Agricultural Warehouse	1	5	28	40	74
	Shed / Storage	12	20	179	192	403
	Garage	5	9	22	24	60
	Comerce facility	0	1	0	0	1
	Industry	0	2	5	8	15
	Uninhabited house	2	4	36	16	58
	Devolute structure	1	3	56	72	132
	Stable	2	1	8	9	20
	Outdoor kitchen	0	2	2	2	6
	Other	2	1	4	4	11
Age of the structure	< 10 years	6	5	2	13	26
	between 10 and 30 years	17	11	26	64	118
	> 30 years	56	58	399	380	893
Type of construction	Concrete	71	57	195	207	530
	Stone	7	14	222	177	420
	Wood	0	0	0	29	29
	Metal	1	2	14	43	60
	Other	0	1	1	1	3

Most of the structures affected by the fire are support structures, such as barracks or storage (38.6%), but there is a considerable number of damaged dwellings, either permanent (13.3%) or temporary (11.9%). The inventoried structures are in general aged, with 86% being older than 30 years, but they are mainly support structures (only 23% of affected houses have more than 30 years). Construction in Portugal is mainly of concrete, but in this area we found many old stone structures. Age and building materials are important factors to be taken into account in the structural strength analysis but are themselves dependent on the degree of conservation or maintenance in which the owners maintain them. During the visits it was possible to observe cases of old houses, mainly of schist, recovered and maintained in excellent conditions (mainly by foreigners), while at the same time relatively recent structures were seen, but with a very low degree of maintenance.

Table 2. Results from the field work related to Results from the field work related to ii) the surroundings of the structure

Variable		Structure condition after the fire				Total
		Slightly damaged	Moderately damaged	Highly damaged	Totally destroyed	
Land use (COS 2010, level 2)	1.1 Urban Tissue	48	39	181	235	503
	1.2 Industry, commerce and transportation	0	1	3	4	8
	1.3 Areas of inert extraction, waste disposal sites and construction sites	0	1	3	1	5
	1.4 Urban green spaces, sports, cultural and leisure facilities, and historical areas	0	0	1	1	2
	2.1 Temporary crops	1	2	4	3	10
	2.2 Permanent crops	4	4	19	18	45
	2.4 Heterogeneous agricultural areas	20	21	152	126	319
	3.1 Forests	4	6	55	58	123
	3.2 Open forests and shrub and herbaceous vegetation	2	0	14	12	28
Fuel Management	Absent	17	20	183	203	423
	Partial	37	40	198	211	486
	Complete	7	8	19	20	54

Analyzing the land use obtained with the level 2 of the official Land Use Map (COS 2010), produced by the Portuguese *Direção Geral do Território* (General Directorate of Territory), it is possible to verify that most of the impact was on the urban areas (50%), specially the urban tissue (48%). The most affected area after this was the one classified as "heterogeneous agricultural areas" (30% of the total). The General Directorate of the Territory (Direção-Geral do Território, 2016) describes these areas as "agricultural areas with various types of associations between temporary crops, pastures, permanent crops and natural areas. Includes temporary crops and/or pastures associated with permanent crops, temporary or permanent crops grown under forest cover, areas of temporary crop mosaics, pastures and permanent crops, and landscapes in which crops and pastures are mixed with natural or semi-natural areas. Only about 11% of damaged structures were within forest areas.

Fuel management is a difficult parameter to assess after the passage of the fire. Nevertheless, and with the help of the local inhabitants, we were able to inventory this aspect in 963 structures. The criteria we used was that, in order to have a “partial” fuel management, at least one of the sides of the structure should have a discontinuity of no less than 3 meters. A “full” fuel management would mean that all 4 sides of the structure had it. Although the results may be statistically not representative, as we did not inventory non-affected houses, they suggest the idea that having “partial” or “absent” fuel management may be indifferent to the structure survival. In other words, either fuel management is active on all the surroundings of the structure or its effectiveness may be compromised.

Table 3. Results from the field work related to iii) the arrival and impact of the fire

Variable		**Structure condition after the fire**				
		Slightly damaged	**Moderately damaged**	**Highly damaged**	**Totally destroyed**	**Total**
Type of ignition	Embers (spotting)	27	54	294	261	636
	Direct fire impact	7	8	91	116	222
	Materials burning on the vicinity	7	9	43	74	133
	Neighbour structure	2	1	3	6	12
	Damaged but no ignition	35	2	1	0	38
Location of the ignition	Roof	16	36	299	293	644
	Window	14	17	70	68	169
	Door	4	7	36	28	75
	Open structure	2	6	13	47	68
	Wall	5	4	0	14	23
	Ventilation	0	1	12	6	19
	Other	3	1	1	0	5
	Damaged but without ignition	35	2	1	0	38

One of the most important aspects of the study relates to the type and location of structural ignition. More than 60% of the structures have been ignited due to the deposition of incandescent particles (firebrands) in different weak points. This percentage could even be higher, as 133 ignitions (12%) were identified as being related to different materials burning in the vicinity of the structure. These were most probably also ignited by embers. More than 60% of these ignitions occurred on the roofs, mainly because of the vulnerability associated to the structures and materials supporting them.

4. Conclusion

The largest impact of this fire complex occurred in the Pedrogão Grande, Castanheira de Pera and Figueiró dos Vinhos municipalities, including small areas in the neighboring municipalities of Penela, Alvaiázere and Sertã. Most damaged structures occurred in this area. These are mainly structures of advanced age (over 30 years), but the majority without being housing. In the fieldwork carried out in the six mentioned counties, we inventoried 263 damaged dwellings (primary and secundary), 91 of which were destroyed. Most ignitions were registered as being originated by firebrands, and mainly affecting roofs and windows. The partial or full absence of fuel management in the surroundings of the houses is a constant in all the burned area. That may explain, in part, the destructive outcome of the Pedrógão fire. Another relevant factor is the observation of the advanced age of most buildings affected (over 30 years), which may indicate less resistance to the passage of a fire. Nevertheless, and for the Portuguese reality, we can say that buildings are generally safe during the passage of a fire, if themselves and their surroundings are kept in good conditions. The fact that there are people inside can even be essential in their defense and resistance to the passage of a wildfire.

5. Acknowledgements

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6. References

Blanchi, R., Leonard, J., Haynes, K., Opie, K., James, M., Kilinc, M., Dimer de Oliveira, F., & Van den Honert, R. (2012). *Life and house loss database description and analysis Final report*. CSIRO, Bushfire CRC report to the Attorney-General's Department. CSIRO EP-129645.

BRP. (2008). *The Blue Ribbon Panel on Wildland/Urban Interface Fire*. Blue Ribbon Panel. International Code Counci (ICC), USA.

Cohen, J. D. (2003). Preventing Residential Fire Disasters During Wildfires. Em G. Xanthopoulos (Ed.), *Proceedings of the International Workshop"Forest Fires in the Wildland-Urban Interface and Rural Areas in Europe: An integral planning and management challenge", May 15-16*. Athens, Greece.

Cohen, J. D., & Saveland, J. (1997). Structure Ignition Assessment Can Help Reduce Fire Damages in the W-UI. *Fire Management Notes*, *57*(4), 19–23. http://doi.org/http://www.firewise.org/wildfire-preparedness/wui-home-ignition-research/the-jack-cohen-files.aspx?sso=d1d65917-4f03-46da-bb5f-0b815f0784ea

Direção-Geral do Território. (2016). *Especificações Técnicas da Carta de Uso e Ocupação do Solo (COS) de Portugal Continental para 1995, 2007 e 2010*. Relatório Técnico. Direção-Geral do Território. Coordenação: Mário Caetano, Cristina Igreja e Filipe Marcelino.

Gollner, M. J., Hakes, R., Caton, S., & Kohler, K. (2015). *Pathways for Building Fire Spread at the Wildland Urban Interface*. Fire Protection Research Foundation.

Graham, R., Finney, M., McHugh, C., Cohen, J., Calkin, D., Stratton, R., Bradshaw, L., & Nikolov, N. (2012). *Fourmile canyon fire findings*. *USDA Forest Service - General Technical Report RMRS-GTR*.

Ribeiro, L. M. (2016). *Os incêndios na interface urbano-florestal em Portugal: uma análise de diagnóstico*. Dissertação para a obtenção do grau de Mestre em Dinâmicas sociais, riscos naturais e tecnológicos. Faculdade de Ciências e Tecnologia da Universidade de Coimbra.

Viegas, D. X., Almeida, M. F., Ribeiro, L. M., Raposo, J., Viegas, M. T., Oliveira, R., Alves, D., Pinto, C., Jorge, H., Rodrigues, A., Lucas, D., Lopes, S., & Silva, L. F. (2017). *O complexo de incêndios de Pedrógão Grande e concelhos limítrofes, iniciado a 17 de junho de 2017*. Centro de Estudos sobre Incêndios Florestais (CEI/ADAI/LAETA).

Westhaver, A. (2016). *Why some homes survived: Learning from the Fort McMurray wildland/urban interface fire disaster*. Toronto, Ontario (Canada): Institute for Catastrophic Loss Reduction Research paper series (56).

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Short contribution – Decision Support Systems and Tools

The relative contributions of climate drivers on extreme Australian fire weather

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Keywords: El Nino Southern Oscillations, Forest Fire Danger Index, spatiotemporal variability

Modes of climate variability have been linked to fire weather around the globe. Variations in sea surface temperatures alter atmospheric circulations, resulting in a change to global distributions of temperature and rainfall. Australia has a high degree of interannual climate variability, modulated by several modes of climate variability. Logically, these modes should also impact the variability of Australian fire weather, but the relationships are not entirely clear. The mechanisms behind this influence, its spatiotemporal variability and the relative contributions of the different climate drivers remain to be understood. Understanding the interactions between climate drivers and Australian fire weather are a step towards improved seasonal forecasts of fire weather, potentially resulting in more effective fire planning and resource management.

In this study, we examine the seasonal relationships of three climate drivers that are known to affect Australia – El Niño Southern Oscillation (ENSO), Southern Annular Mode (SAM) and Indian Ocean Dipole (IOD) with the annual cumulative and seasonal 90th percentile McArthur Forest Fire Danger Index (FFDI) at 39 locations across Australia. We also determine the relative contributions of the climate drivers using partial correlations and regression analysis, as well as considering the seasonal lag effect.

We find that the relationship between ENSO and extreme fire weather (90th percentile of FFDI) is significant and widespread across most of the country throughout winter, spring and summer. The strongest values occur in spring and the relationship with cumulative fire weather is stronger than with the concurrent seasonal extreme fire weather. Considering the lag relationships with ENSO indices there is high predictability for both one- and two- seasons in advance for the summer FFDI for most of the country. This is important because this is a critical high fire danger period for southern and eastern states. Additionally, predicting spring FFDI is possible for many parts of the country up to one season in advance. This is particularly important for early season fires that have been found to occur in New South Wales(NSW)/Australian Captial Territory (ACT), although ENSO was not statistically significant along the coast. For the autumn period there is some ability to predict fire weather in the NSW/ACT region; this may be useful for prescribed burning planning or for late season bushfires. Finally, in the winter months there is some predictability of FFDI for northern parts of Australia, which is useful as this is the beginning of their peak burning period. Overall, the relationship between cumulative FFDI and ENSO was stronger than for those found between seasonal extreme fire weather.

For SAM, extreme fire weather in the inland areas across Australia is significantly related to SAM in autumn, however for all other seasons SAM is strongly related to fire weather across the eastern states, with the peak occurring in spring and highest values across coastal NSW. When lag seasons are considered for SAM there appears some advanced predictability for the summer fire weather for the south east of the country, particularly Victoria, Tasmania and South Australia (AS). A negative SAM in the spring results in higher FFDI values in summer. Additionally, for the spring fire weather there is some predictability one season in advance for northern NSW and southern Queensland (QLD). Overall seasonal SAM is more strongly related to seasonal extreme fire danger than to cumulative fire danger.

The relationship between IOD and extreme fire weather in winter is patchy across southern Australia with the strongest relationships in the west. In spring the relationship is stronger and concentrated in the south east of the country including stations from NSW/ACT, Victoria, SA and Tasmania. There are both one- and two-season lag relationships with summer extreme fire danger in Tasmania. The cumulative fire danger is not as strongly related with IOD as extreme fire danger but there are more stations with cumulative FFDI significantly related to IOD in Western Australia (WA) during spring than was found for extreme fire weather during the same period.

When the combined effect is considered to identify the dominant drivers we find in autumn SAM dominates central and western stations and ENSO has a weak relationship with stations in the south east of NSW/ACT. In winter the IOD is the dominant driver over the south of SA, the south and western coast of WA along with northern Australia. ENSO dominates much of north central Northern Territory (NT) and QLD along with NSW, whereas SAM dominates some of the stations in southern QLD, parts of NSW and Tasmania. In spring, the whole of QLD extending across central Australia is dominated by ENSO whereas SAM dominates NSW, and IOD dominate in parts of SA and Tasmania. In spring for Victoria there are no dominant drivers when the combined effect are considered suggesting that extreme fire weather requires the combined effect of IOD and ENSO to predict the variability. However, the relationship between IOD in winter with winter FFDI values is stronger than ENSO for WA and SA (with the exception of the inland SA site of Woomera). In summer, for the combined drivers, (noting that IOD is not included during this period) ENSO dominates most of the country particularly the Eastern coastal regions with the exception of SAM, which is the dominant driver in north east of NSW. When considering the lag effect of spring climate drivers on summer extreme fire weather ENSO dominates the entire eastern coast extending up to Darwin and also dominates in central WA. Whereas, SAM is the dominant climate driver across SA, Victoria and Tasmania. Their annual results also indicate that other drivers dominate over the rest of the state, which corresponds to the locations of the two Tasmania stations in this study, particularly IOD and ENSO in the north of the state (where Launceston AP is located). Overall, SAM and ENSO have little impact on the independent relationships with fire weather, however ENSO and IOD are not independent of each other in relation to fire weather.

Our study demonstrates that using a varying combination of climate drivers throughout each season there is considerable potential for producing long-range seasonal forecasts of fire weather. This advanced warning of fire weather may be useful for fire agencies making decisions around resource allocation and risk management.

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Short contribution – Decision Support Systems and Tools

Understanding fire, weather and land cover interactions from long-term terrestrial observations and satellite data on a transect from Europe to North Africa

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Keywords: Long-term documented historical fire records, Switzerland, Greece, Algeria, Tunisia, remote sensing, generalized linear models, extremes, climate, fire selectivity.

1. Project overview

Long-term historical time series records of fire activity (number of fires and total area burned) extending back to the late 1800s, that are very rare worldwide, were found and used within the GRADIENT project that correspond to (i) Switzerland, central Europe (1900-2014), (ii) Greece, south Europe (1897-2014), (iii) Algeria, north Africa (1870-2014) and (iv) Tunisia (1902-2015), north Africa which together with the spatial-explicit reconstruction of recent fire history from Landsat satellite images (1984-2016), gave a unique and excellent opportunity to understand fire, weather and land use/land cover (LULC) interactions in a north to south transect. The Tunisia study case was added during the implementation period of the project since in the original proposal only the first three study cases were proposed.

Differences in bio-geographical characteristics provided by the four selected study areas, located on a large geographical gradient covering two continents gave the opportunity to document the role of fire in different biomes, to explore cross-scale issues and assess how fire-weather-LULC interactions vary across different scales, especially under a climate change context. GRADIENT project consisted of three topics that correspond mainly to three different scales. The specific objectives were: (i) the identification of trends, patterns and relationships between forest fires, weather, land cover and socio-economic variables from long-term observations, (ii) the reconstruction of recent fire history and the assessment of burning patterns and fire selectivity on an annual basis from satellite images, and (iii) the exploration of post-fire vegetation dynamics and recovery for selected large fire events using time series satellite images.

1.1. Trends, patterns and relationships between forest fires, weather, land cover and socio-economic variables

There are similarities and non-similarities among the four study area that compose the gradient from north to south. In principle there is a characteristic fire activity in all four study areas defined by the general pyro-environment with certain peaks occurred at specific years associated to physical and social factors. The role of precipitation is different in the gradient from the wet to dry areas. Moisture is more evident as an underlying explanation mechanism in the wet study area while temperature is more evident in the dry study areas. It was evident that there is a clear and different role of precipitation from promoting to discouraging fire activity across the north to south gradient together with the social aspects and the role of human dimension.

Concerning the extremes, two clear patterns were observed according to the two discrete roles of the explanatory variables recognized previously; the first pattern where the role of the explanatory variable is to promote fire activity as the example of Switzerland with the effect of precipitation or dry period area promoting fires (e.g. drought) and the second pattern where the role of the explanatory variable is to discourage fire activity as the example of Greece or Algeria with the effect of precipitation or dry period area discouraging fires (e.g. wet conditions). We recognize a gradient from north (Switzerland) to south (Algeria) where the role of explanatory variable to fire activity is changing from promotion to discourage.

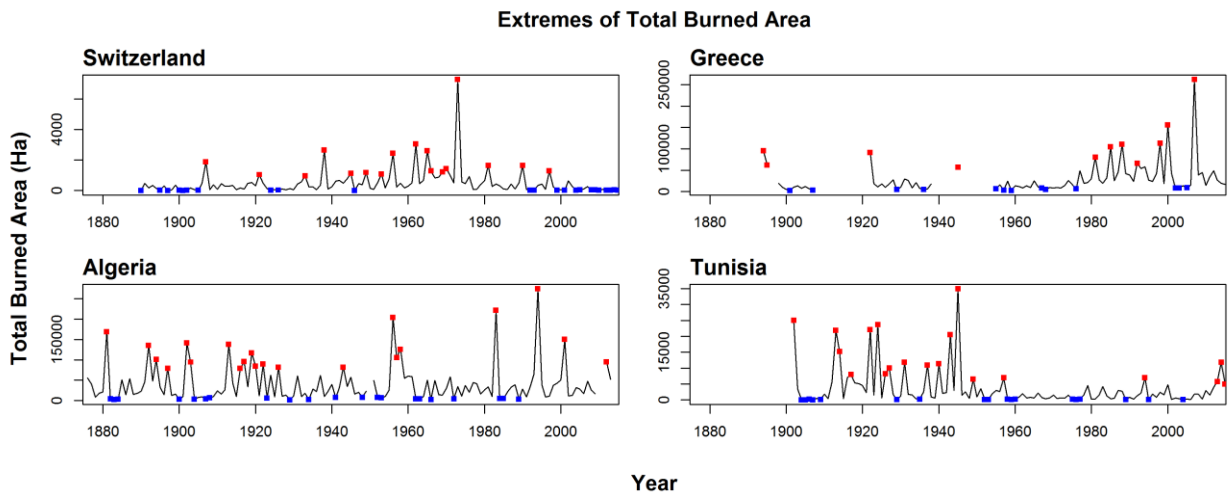

Figure 1 - The extreme years for both high and low fire activity at yearly basis for the four study areas. The distribution of the extreme years is similar to all countries: 14-18% is the range of the high extremes, 12-17% is the range of the low extremes and 67-74% is the range of the non-extremes which is the majority.

1.2. Reconstruction of recent fire history and the assessment of burning patterns and fire selectivity

The interactions of landscape components and fire were analyzed by comparing the relative proportions of what the fires burnt during the period 1984-2015 against what is available to burn across the landscape (e.g. CORINE, or other available global land cover data, e.g. ESA global land cover data), considering a random model that accounts for spatial autocorrelation. To determine whether the wildfires burn significantly different proportions of LULC classes than what is available to burn we applied a Monte Carlo randomization test considering spatial autocorrelation on the basis of randomizing the fire events using however the exact fire shape to account for the spatial autocorrelation. For all study area selective burning is evident that also depends on the available to burn landscape. Frequent fires were also observed that burn mainly grassland and shrublands.

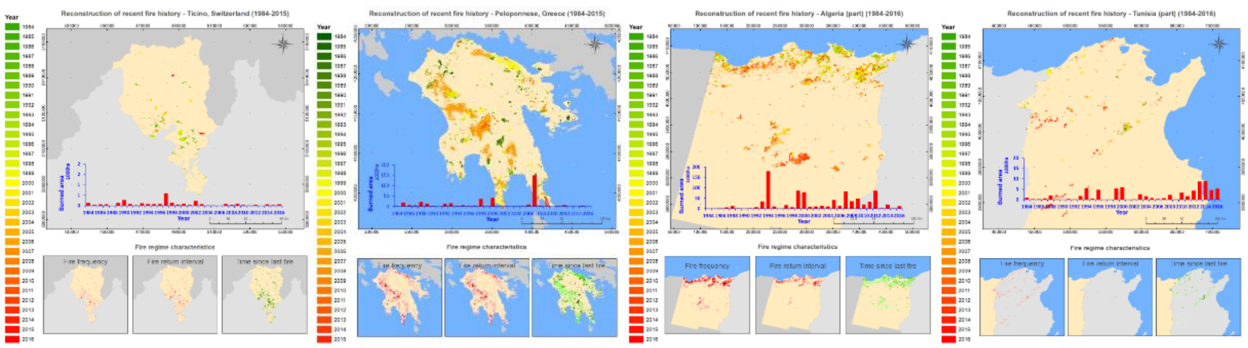

Figure 2 - Fire regime characteristics depicting (i) fire scar maps that include patterns of burned and unburned patches, (ii) fire frequency, (iii) fire return intervals, and (iv) time since last fire event.

1.3. Exploration of post-fire vegetation dynamics and recovery using time series satellite images

Satellite remote sensing data from MODIS and LANDSAT satellites in the period from 1984 to 2016 were acquired and processed to extract the temporal profiles of the spectral signal for selected areas within the fire-affected areas. This dataset and time period analyzed together with the time that these fires occurred gave the opportunity to create temporal profiles for almost half years before and half years after the fire. The different scale of the data used gave us the chance to understand how vegetation phenology and therefore the recovery patterns are influenced by the spatial resolution of the satellite data used.

Within the GRADIENT project vegetation phenology and time series statistics proved very useful not only to study vegetation recovery in fire affected areas but also to identify the time period where the fire or fires occurred and define also the vegetation phenology before the fire. This is very useful first for integrating this concept into a burned land mapping approach and second for identifying what type of vegetation is burned.

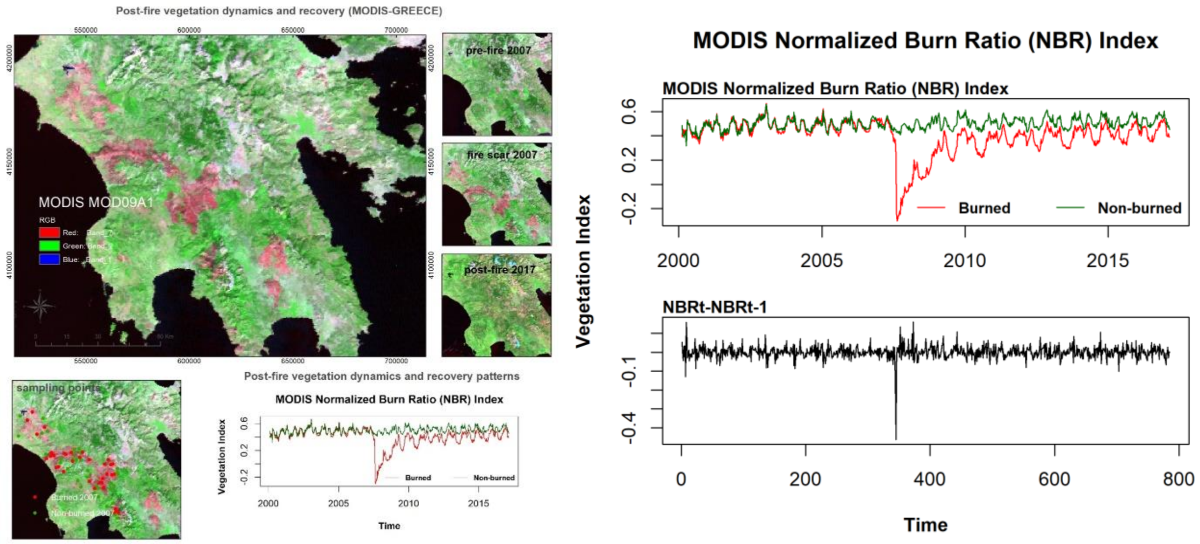

Figure 3 - Vegetation recovery of a 2007 fire in Greece using the phenology from the time series MODIS data. The date of fire occurrence is very well defined in the NBRt-NBRt-1 time series.

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Short contribution – Socio Economic Issues

Does it pay to invest in better suppression resources? – policy analysis of alternative scenarios with simulation

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Abstract

Rekindles (RKD) and false alarms (FA) are unusually high in the Portuguese wildfire management system. Together they represent a high burden on suppression resources in particular, and fire management resources in general. Indeed, e.g., during 2010, according to data provided by the Portuguese Institute for Nature Conservation and Biodiversity (ICNF), in 20,049 occurrences that the suppression system handled in the summer, 12.5% were FA and 15.0% were RKD.

During the fire season, it is usual to have large usage of suppression resources to combat wildfires and on peak days, firefighters are in a tight spot due to the pressure to move incessantly from one fire to the next one. In such occasions the system may not be able to effectively meet the needs, getting out of control. If there are fires waiting to be fought, suppression crews are pressured to prematurely abandon mop-up operations (moving towards the initial attack of new fires), without the needed time to use the appropriate tools to effectively carry out mop-up. When one of these fires with a bad mop-up rekindles, it is one more to join the other new ignitions or primary fires, and they are generally more aggressive than the latter.

We first developed a discrete-event simulation model of a wildfire suppression system, designed to analyze the joint impact of primary fires, RKD and FA on the system performance. Recently (unpublished), we explicitly closed the causal loop between primary fires and RKD, and modeled the suppression resources in greater detail, by distinguishing standard crews of volunteer firefighters (with and without training) from expert crews of professional firefighters. Using a Portuguese district as case study, with a set of scenarios, we analyzed the cost-effectiveness of investing in the training of standard and/or expert crews, considering different dispatch policies.

We found that reducing FA and RKD to benchmark values would significantly reduce pressure on firefighting teams, enabling more effective suppression operations, and that it pays to invest in better suppression resources.

Keywords: Forest Fire Suppression, Rekindles, False Alarms, Cost-Effective Analysis, Discrete Event Simulation

1. Introduction

Rekindles (RKD) and false alarms (FA) are unusually high in the Portuguese wildfire management system. Together, they represent a high burden on suppression resources in particular, and fire management resources in general. Indeed, e.g., during 2010, according to data provided by the Portuguese Institute for Nature Conservation and Biodiversity (ICNF), in 20,049 occurrences that the suppression system handled in the summer, 12.5% were FA and 15.0% were RKD (Pacheco *et al.* 2014c).

During the fire season, it is usual to have large usage of resources (human and material) to combat wildfires and, on peak days, firefighters are in a tight spot, due to the pressure to move incessantly from one fire to the next one (Beighley and Hyde 2009). In such occasions, the system may not be able to effectively meet the needs, getting out of control. If there are fires waiting to be fought, they keep spreading, becoming harder to extinguish, with an increased likelihood of becoming mega-fires, reaching people, homes and animals, besides destroying the forest landscape (Lourenço and Rainha 2006). Consequently, pressured suppression crews prematurely abandon mop-up operations (moving towards the initial attack of new fires), without the needed time to use the appropriate tools to effectively carry out mop-up. When one of these fires with a bad mop-up rekindles, it is one more to join the other new ignitions or primary fires, and they are generally more aggressive than the latter (Pacheco *et al.* 2012; Pacheco *et al.* 2014a).

2. Materials and Methods

We first developed a discrete-event simulation model (implemented in ®ARENA) of a wildfire suppression system, designed to analyze the joint impact of primary fires, RKD and FA on the system performance (Pacheco *et al.* 2014b).

	STD crews *(not specialized)* without extra training (*as is*)	with more training	**EXPRT crews** *(specialized)*	**K**	**P**	**Description**
Scenario 0	100%		0%	1	*not applicable*	100 crews
Scenario 1	100%		0%	1	*not applicable*	Variation in the number of crews
Scenario 2	0%	100%	0%	]0,1[	*not applicable*	100 crews (with training)
Scenario 3	80%		20%	1	1%, 3%, and 6%	Variation of the failure probability (p) of EXPRT crews
Scenario 3 (composition)	80% 60% 40% ...		20% 40% 60% ...	1	3%	Variation in the crew composition
Scenario 4	z%		1 – z%	1	3%	With different "z%", three dispatch policies tested

Figure 1 - Battery of tests performed with the ®ARENA simulation model.

This model contributes to fill a research gap concerning that impact, and features a novel application of simulation to suppression systems, as screening tools to support more holistic analyses. Recently (unpublished paper), we explicitly closed the causal loop between primary fires and RKD, and modeled the suppression resources in greater detail, by distinguishing standard crews of volunteer firefighters (with and without training) from expert crews of professional firefighters.

We use a Portuguese district as case study, and with a set of scenarios (please see Figure), we analyzed the cost-effectiveness of investing in the training of volunteer firefighters and/or using expert crews of professional firefighters, under different dispatch policies.

Our model aims to support the analysis of the impact of different forest fire suppression policies on rekindles and false alarms and these policies are based on the existence of different types of suppression crews: volunteers (as-is), volunteers with more training, and professional firefighters.

3. Results

We found that reducing FA and RKD to benchmark values would significantly reduce pressure on firefighting teams, enabling more effective suppression operations, and that it pays to invest in better suppression resources (Pacheco *et al.* 2014b).

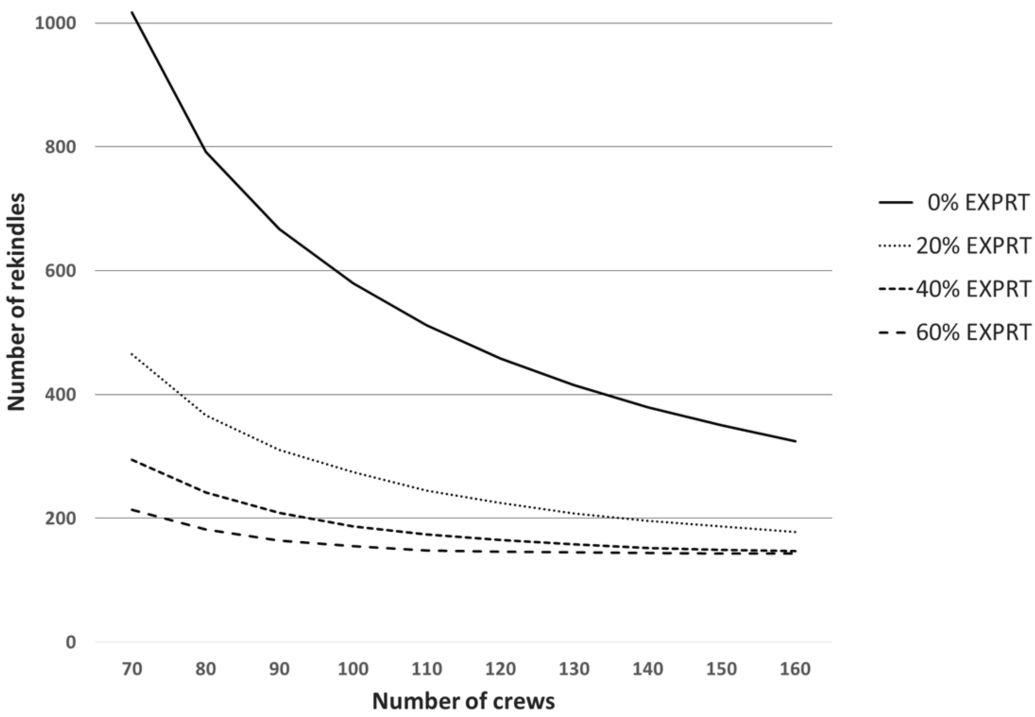

Figure 2 - Example of the kind of results obtained, in this case the evolution of rekindles by changing the percentage of professional crews (EXPRT).

The results of the cost assessment (e.g., Figure) for the different scenarios (in Figure) indicate that modifying the current (fixed) system design to a more flexible one, mixing volunteer firefighters with professional firefighters and/or investing in the training of the volunteers, appears to offer good prospects in terms of improving forest fire management, as more fires with a good mop-up will lead to fewer rekindles and thus, less pressure over the firefighting crews.

Finally, the eventual increase in the system costs must be weighed against the benefits resulting from the damage avoided with fewer rekindles.

4. Acknowledgements

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5. References

Beighley, M, Hyde, AC (2009) Systemic Risk and Portugal's Forest Fire Defense Strategy: An Assessment of Wildfire Management and Response Capability.

Lourenço, L, Rainha, M (2006) As mediáticas 'mãos criminosas dos incendiários' e algumas das 'lições dos fogos florestais de 2005 em álbum fotográfico. Contributo para a desmistificação dos incêndios florestais em Portugal. *Territorium* 71-82.

Pacheco, AP, Claro, J, Oliveira, T (2012) Rekindle dynamics: validating the pressure on wildland fire suppression resources and implications for fire management in Portugal. In 'Modelling, Monitoring and Management of Forest Fires III.' Vol. 3 pp. 258. (Wessex Institute of Technology: Ashurst, Southampton, UK)

Pacheco, AP, Claro, J, Oliveira, T (2014a) Rekindles or one-σ quality in forest fire fighting: validating the pressure on firefighters and implications for forest fire management in Portugal. In 'Advances in forest fire research.' (Imprensa da Universidade de Coimbra: Coimbra)

Pacheco, AP, Claro, J, Oliveira, T (2014b) Simulation analysis of the impact of ignitions, rekindles, and false alarms on forest fire suppression. *Canadian Journal of Forest Research* **44**, 45-55.

Pacheco, AP, Claro, J, Oliveira, T (2014c) Waste in non-value-added suppression activities: simulation analysis of the impact of rekindles and false alarms on the forest fire suppression system. In 'Advances in forest fire research.' (Imprensa da Universidade de Coimbra: Coimbra)