ADVANCES IN FOREST FIRE RESEARCH

2022

Edited by
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The role of the fuel moisture content on the prediction of large wildfires using the Fire Weather Index system

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Keywords

Wildfires, Fuel moisture content, fire danger, FWI, prediction

Abstract

Fuel moisture content is one of the fundamental parameters in forest fire research and management given its implications for many aspects of fire danger systems. In Portugal, such as in many other countries, to classify the days with more favourable conditions for wildfires it is common to use the Canadian Forest Fire Weather Index System (CFFWIS) which is based on the estimation of moisture content of several fuel components. The mathematical structure of CFFWIS requires as input the daily meteorological parameters which are used to estimate the moisture content of the soil for different layers that are the primary outputs of the system – the fire moisture codes. The final output parameter of the system is the Fire Weather Index (FWI) which represents a measure of the fire danger due to meteorological conditions.

The temporal scale of the study is from 2018 and 2021 and the study area is in Lousã, a central region of Portugal. In this work, in addition to the meteorological data, we will use as input the direct measurements of dead fuels in the CFFWIS and analyse its influence on the FWI. The fuel moisture content (m_f) is determined through the sample collection of dead pine needles in Lousã. For this temporal scale, m_f by sampling is significantly lower than the modelled m_f using meteorological parameters. An advantage of using the m_f measurements is to increase the range of FWI variation, giving a higher sensitivity to the index to more easily discriminate the days with high fire danger and large burned areas. Two methods are addressed: "FWI a" which represents the traditionally FWI determined only by meteorological parameters, and the "FWI b" which is determined with fuel moisture content measurements and with meteorological data for the days that we did not have measurements.

The original FWI, based only meteorological parameters, is compared with the FWI determined using m_f measurements. The different methods will be related with the number of fires and burned area to analyse their performance. The results show a good fit between m_f and FWI for days with extreme weather conditions (m_f<5%).

1. Introduction

Fuel moisture content is determinant in the extension of the burned area (Lopes, 2013; Viegas et al., 2017) being a fundamental parameter in wildfire research and management given its implications for many aspects of fire danger. Recent work found that high values of the Fine Fuel Moisture Code (FFMC) may determine when large fires can occur, supporting close relationships between moisture thresholds and fire behaviour (Carmo et al., 2021). The assessment of fuel moisture content reveals to be crucial for the characterization of extreme fire events allowing the improvement of early warning systems over extreme weather conditions.

Traditional fire danger systems rely on meteorological indices, based on variables that are routinely measured on weather stations (Chuvieco et al., 2010). To estimate the fire danger in Portugal, as in Europe (Viegas et al. 1999), it is common to use the Canadian Forest Fire Weather Index System (CFFWIS) developed by Van Wagner (1987). The CFFWIS produces the Fire Weather Index (FWI) which is a composite index that represents the meteorological conditions and gives an indication of the expected fire intensity (Van Wagner 1987). The structure of CFFWIS is presented in Figure 1.

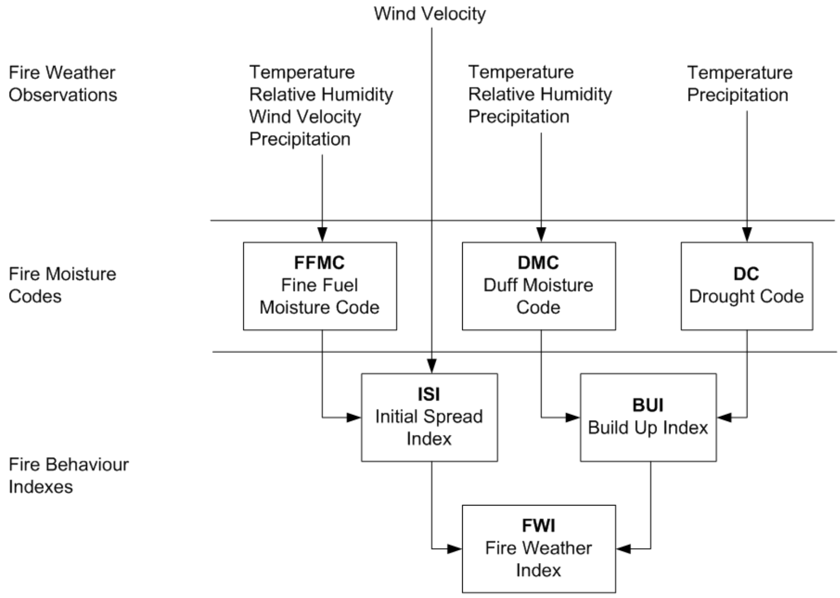


Figure 1 - Structure of CFFWIS by Van Wagner 1987.

The basis of this system is the prediction of dead fuel moisture content based on a set of physical equations calculated through meteorological data that are the input parameters (see Figure 1). The intermediate outputs are respective to fire moisture codes: Fine Fuel Moisture Code (FFMC) is associated to the surface litter, the Duff Moisture Code (DMC) is associated to the duff layers about 7cm deep, and the Drought Code (DC) is associated to the soil layers about 18cm deep and is well correlated with live moisture content (Viegas et al., 2001). The intermediate outputs of the system are the fire behaviour indices: Initial Spread Index (ISI) and Build-Up Index (BUI) giving a relative indication of the initial fire spread after the ignition and of the availability of the fuel to participate in fire propagation, respectively. These indices are combined to provide the final output parameter of the system – the Fire Weather Index (FWI), which represents the expected intensity of a spreading fire. The indices are cumulative as they take into consideration the effect of weather conditions in the previous days. The increase in each of these components corresponds to an increase of fire danger. These meteorological indices have some limitations when applied to other regions than that led to its formulation, namely they do not provide a real quantitative assessment of fuel moisture content value and therefore need to be validated with local data.

Based on the model used to calculate the CFFWIS, an approach to analyse the role of fuel moisture content on large wildfire occurrences will be addressed. We intend to analyse how FFMC changes when it is determined through direct measurements of fuel moisture content (m_f) and, consequently, how FWI changes.

The study is based on m_f measured in Lousã, a central region of Portugal. The analysis focuses exclusively on dead fine fuels, leaving aside the dynamics of live fuel with fire. In this paper the time period from 2018 to 2021 (4 years) is considered.

2. Methodology

2.1. Determination of the m_f

The fuel moisture content is determined by sample collection of several species in a field plot located in Lousã near the Forest Fire Research Laboratory (LEIF) – Figure 2.

(a) (b)

Figure 2 – (a) Local of the sampling area, Forest Fire Research Laboratory (LEIF), weather station and (b) their position in the Portuguese territory.

In LEIF, the samples are weighed with 5g each (initial mass: m_i), they are dried in an oven (24h and 105ºC) and their dry mass: m_d is determined. Fuel moisture content, $m_{f_{sampling}}$, in a dry basis is determined by Equation 1.

$$m_{f_{sampling}} = \frac{m_i - m_d}{m_d} \tag{1}$$

For this analysis, the m_f measurements of pine needles of *Pinus Pinaster* are used.

Figure 3a presents the relation of the m_f modelled in the CFFWIS ($m_{f_{meteo}}$) and the m_f observed ($m_{f_{sampling}}$) for all data (450 days). Figure 3b) presents the distribution of both m_f (modelled and observed) among the study period.

a) b)

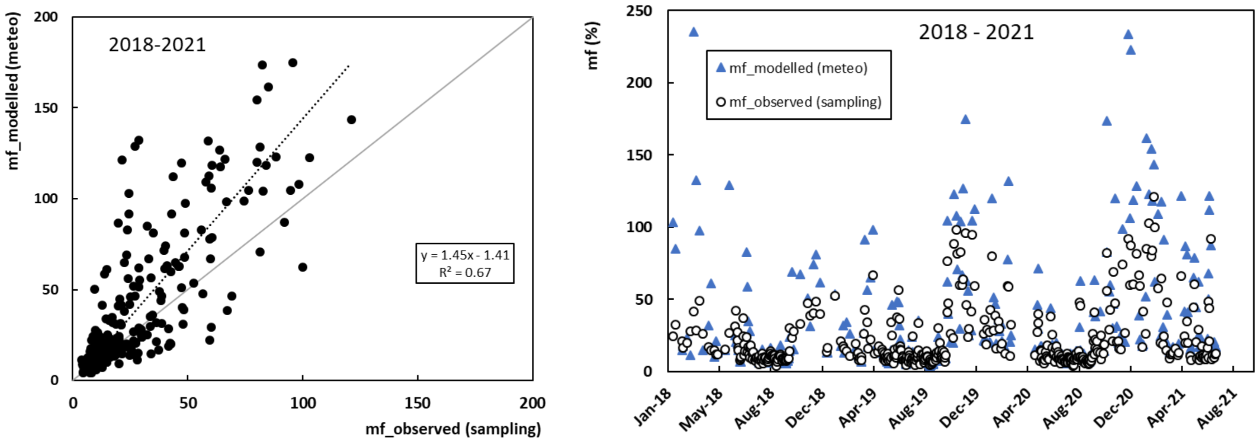


Figure 3 – a) Relation of the $m_{f_{meteo}}$ proposed by Van Wagner (1987) with the observed $m_{f_{sampling}}$ in Lousã; b) Distribution of the $m_{f_{meteo}}$ and the o $m_{f_{sampling}}$ per day.

Both figures show that the range of values for observed m_f is lower than the range values for modelled m_f.

Between 2018 and 2021 and considering all data (n=450), the sample mean for $m_{f_{sampling}}$ and $m_{f_{meteo}}$ was 20.47% and 28.36%, respectively. A "T-test for Equality of Means" was done using the statistical software

SPPS (28) to verify if the $m_{f\,sampling}$ is significantly lower than the $m_{f\,meteo}$. The following test hypothesis were done:

- H0: $m_{f\,sampling}$ mean = $m_{f\,meteo}$ mean;
- H1: $m_{f\,sampling}$ mean < $m_{f\,meteo}$ mean.

Output of the test is presented in Figure 4.

Independent Samples Test

		t-test for Equality of Means							
				Significance				95% Confidence Interval of the Difference	
		t	df	One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	Upper
mf	Equal variances not assumed	4,09	708,88	<,001	<,001	7,88	1,93	4,10	11,67

Figure 4 – Output of the "T-test for Equality of Means" between two independent variables: $m_{f\,sampling}$ and $m_{f\,meteo}$.

The test has a p-value <0.001, so for any usual significance level (0.01< α< 0.1) we reject the null hypothesis (H0) and we keep the one-sided alternative hypothesis (H1). The $m_{f\,sampling}$ is significantly lower than the modelled $m_{f\,meteo}$. An advantage of using the m_f measurements, since they have lower values, is to increase the range of FWI variation, giving a higher sensitivity to the index to more easily discriminate the days with high fire danger and large burned areas.

2.2. Determination of the FFMC

The function defined by Van Wagner (1987) relating FFMC with the moisture content of the surface fuels is presented in Equation 2. In this equation $m_{f\,meteo}$ is estimated by meteorological data.

$$FFMC = 59{,}5 \times \frac{250 - m_{f\,meteo}}{147 + m_{f\,meteo}} \qquad (2)$$

Viegas et al. (2004) have developed a calibration function that uses FFMC to estimate the m_f (Equation 3) for dead fuels in the Portuguese forests.

$$m_f = 9 \times 10^9 \times FFMC^{-4.56} \qquad (3)$$

In Figure 5 data of m_f obtained in the study period is plotted as function of FFMC measured at Lousã. The curves corresponding to equations 2 and 3 are plotted in the Figure 5.

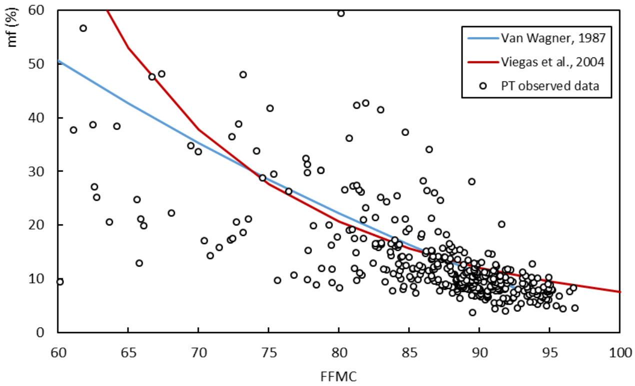


Figure 5 – Relation between m_f and the FFMC in Lousã – PT observed data. Functions proposed by Van Wagner, 1987 and Viegas et al., 2004.

The m_f measurements to be used in this study are distributed according to both models.

Figure 6 presents the relation of the m_f determined for each model (Van Wagner (1987) and Viegas et. al. (2004) with m_f measurements in Lousã (observed data) for values of mf<30% (335 days).

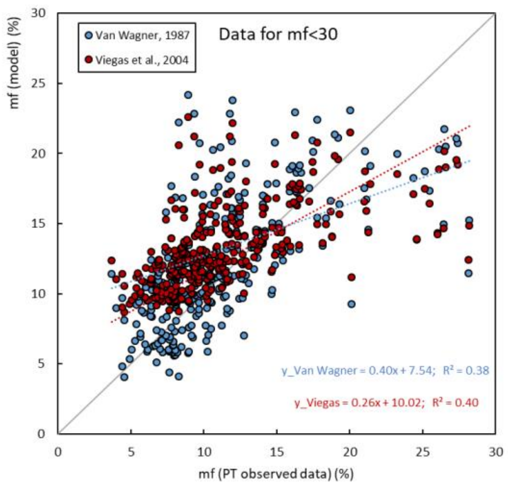


Figure 6 – Relation of the m_f proposed by Van Wagner (1987) and Viegas et al. (2004) with the m_f measurements in Lousã (observed data).

Both models have a similar relation with the observed data and similar coefficients correlation. We will maintain the Equation 2 to determine FFMC since its validity was verified for the Portuguese data and it is the original equation of the FWI system.

2.3. Determination of the FWI

Two methods are addressed to determine the FWI value:

a) FWI calculated as defined in Van Wagner, 1987 (only meteorological data).
b) FWI calculated with m_f measurements - m_f is used as input parameter in the FFMC calculation through Equation 2; the remaining moisture content codes (DMC and DC) are determined using meteorological data as defined by Van Wagner. After this step the system runs according with Van Wagner equations giving the final output – FWI.

2.4. Relation of the results with the number of fires and burned area

In order to calibrate the different methods (***FWI a*** and ***FWI b***) in terms of number of fires (NF) and burned area (BA) we used the fire history of the municipalities surrounding Lousã (Coimbra, Miranda do Corvo, Penacova, Góis, Penela, Vila Nova de Poiares, Arganil e Pampilhosa da Serra) as presented in Table 1.

Table 1 – Municipalities surrounding Lousã considered to calibrate the methodology regarding the number of fires (NF) and burned area (BA) between 2018 and 2021. Source: NF and BA provided by ICNF.

Municipality (area)	NF (2018-2021)	BA (ha) (2018-2021)
Lousã (138.40 km²)	32	11.6
Coimbra (319.40 km²)	159	21.0
Miranda do Corvo (126.38 km²)	44	570.4
Penacova (216.73 km²)	5	1.5
Góis (263.30 km²)	27	2.8
Penela (132.49 km²)	35	5.8
Vila Nova de Poiares (84.4 km²)	9	0.9
Arganil (332.84 km²)	36	5.1
Pampilhosa da Serra (396.46 km²)	22	26.8

We followed the methodology proposed in Viegas et al. (2004) and replicated in Alves et al. (2018, 2021) that requires the following parameters:

- Daily FWI values;
- Daily NF, and
- Daily BA.

A new field called Probability (P) was determined (Equation 4). This field reflects the weight that a given day (and its respective FWI) has in respect to the total number of days. The higher the FWI, the higher the "incremental day" and the higher the respective "probability" of occurrence of values of FWI.

$$P = \frac{Incremental\ day}{Incremental\ day\ total} \qquad (4)$$

After the ***P*** calculation we need to categorize the probability into classes which is equivalent to splitting the results by percentiles. For each one was calculated: maximum FWI value that limits the class, average FWI value, average of number of fires and average of burned area.

NF and BA, in terms of average values, were related with the original FWI (***FWI a***) and with the FWI calculated with m_f measurements (***FWI b***).

3. Results and discussion

In Figure 7 the relationship between the ***FWI a*** and ***FWI b*** is presented***,*** as well as the respective correlation coefficient (R^2).

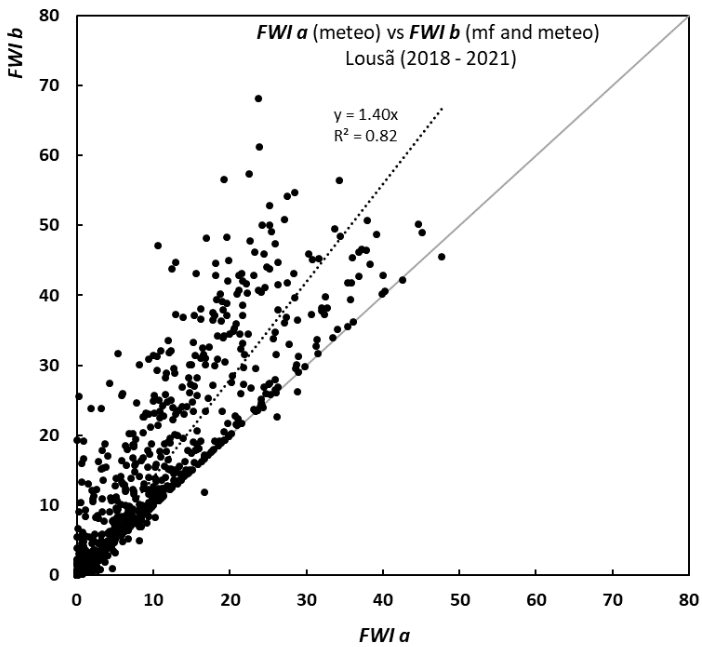


Figure 7 – Function of the original FWI calculated (FWI a) and FWI with m_f measurements (FWI b)

In Figure 7, the results show a good relationship between the two methods since the linearity is evident (high correlation coefficient) but the ***FWI b*** has higher values than the ***FWI a***.

Figure 8 presents an example of the values obtained for the two methods (***FWI a*** and ***FWI b***) for the main season in 2020 (15 May – 30 September). Also presents the values of m_f measurements in the secondary axis for the same period.

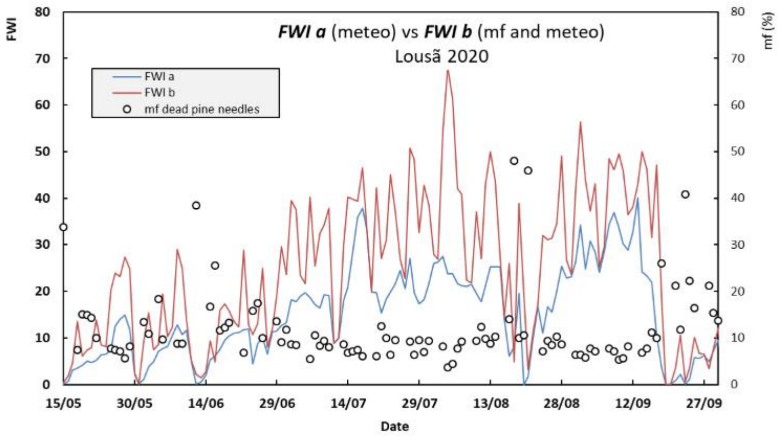


Figure 8 – Original FWI (FWI a) and FWI with m_f measurements (FWI b) – principal axis; m_f measurements – secondary axis.

The results show some differences between the two methods. FWI determined with direct m_f measurements were higher for days considered with "extreme conditions" since the m_f in Lousã was lower than 5% (Viegas et al., 2017). For example, on 4th of August, the m_f was 3.68% and for that day ***FWI a*** was 24 (high level according with Viegas et al., 2004 and EFFIS-JRC, 2022) while the ***FWI b*** was 70 (extreme level according with the same studies).

In Figure 9 is presented the average values of FWI determined for each percentile and the threshold for each danger class: low, moderate, high, very high and maximum.

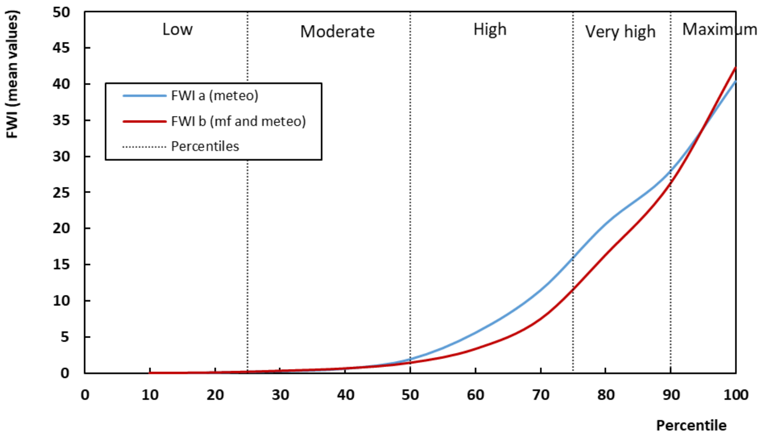
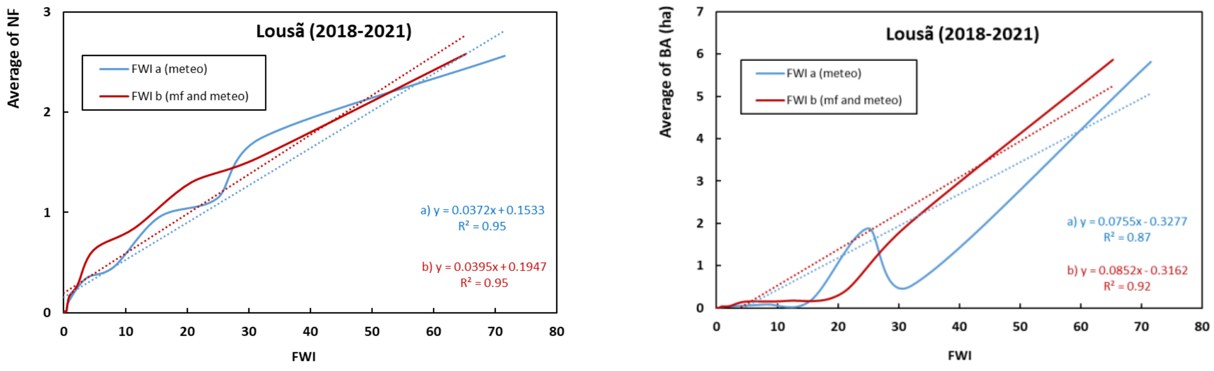


Figure 9 – Mean values of "FWI a" and mean values of "FWI b" calculated for each percentile. The vertical dotted lines define the threshold for each danger class: low, moderate, high, very high and maximum. "FWI a" is the FWI original calculated; and "FWI b" in the FWI with mf measurements.

The distribution of the two methods is similar in the begin, but from P50 to P90 the FWI ***a*** is higher than the ***FWI b***. Around P95 the ***FWI b*** presents higher values which highlights the importance that direct *mf* measurements can have for the maximum fire danger classes. The measurements can have a higher effect on the numerical value of the FWI but this effect is "hidden" with the other codes (DMC and DC) that do not consider the real m_f measurements. As a future work, we propose the measurement of soil moisture at different depths and its inclusion in the calculation of DMC and DC.

Figure 10a) presents the relation of the two methods (***FWI a*** and ***FWI b***) with the number of fires and Figure 10b) presents the relation with the burned area. In both figures, the solid lines represent the real data and the dotted lines represent the correlation equation.



(a) (b)

Figure 10 – a) Relationship between FWI and the number of fires (NF); b) relationship between FWI and the burned area (BA).

The methods (***FWI a*** and ***FWI b***) have a similar behaviour for the NF (Figure 10a)), but for the BA the method considering m_f (***FWI b***) has a higher correlation coefficient than the method using only meteorological data (***FWIa***). In Figure 10b) it is verified that for FWI < 10 ***FWI a*** and ***FWI b*** are similar, but for high values of FWI, the ***FWI b*** crosses the ***FWI a*** curve and starts to represent larger burned areas, demonstrating the potentiality of using real measurements to represent the fire danger in terms of BA.

Figure 10 is an example for the calibration results that is typically made for this data, but we only considered the municipalities surrounding Lousã for 2018-2021.

4. Conclusion

Fuel moisture content is determinant in the extension of the burned area being a fundamental parameter in many aspects of fire danger.

The fire danger system used in Portugal – the Fire Weather Index (FWI), considers moisture indices or codes in their mathematical routine but estimates them through meteorological data. We presented a methodology to study the role that direct measurements of fuel moisture content can have in the FWI and its potentialities to predict large wildfires. Two methods were addressed: "***FWI a***" which represents the traditionally FWI determined only by meteorological parameters, and the "***FWI b***" which was determined with fuel moisture content measurements and with meteorological data for the days that we did not have measurements.

The fuel moisture content measurements,m_f, of dead pine needles collected in Lousã were used between 2018 and 2021. The preliminary results show that measurements can improve the FWI system to days with extreme weather (m_f<5%) since the FWI achieve higher values for lower m_f values. Also, the correlation between FWI considering m_f and burned area contributes to increase the correlation between the variables. Regarding the relation with number of fires seems to have not much differences between using only meteorological data or considering real measurements.

We will consider in future studies the extension of the temporal scale and the analysis of the dead eucalyptus leaves since they are also represent the dead blanket of Portuguese forests.

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