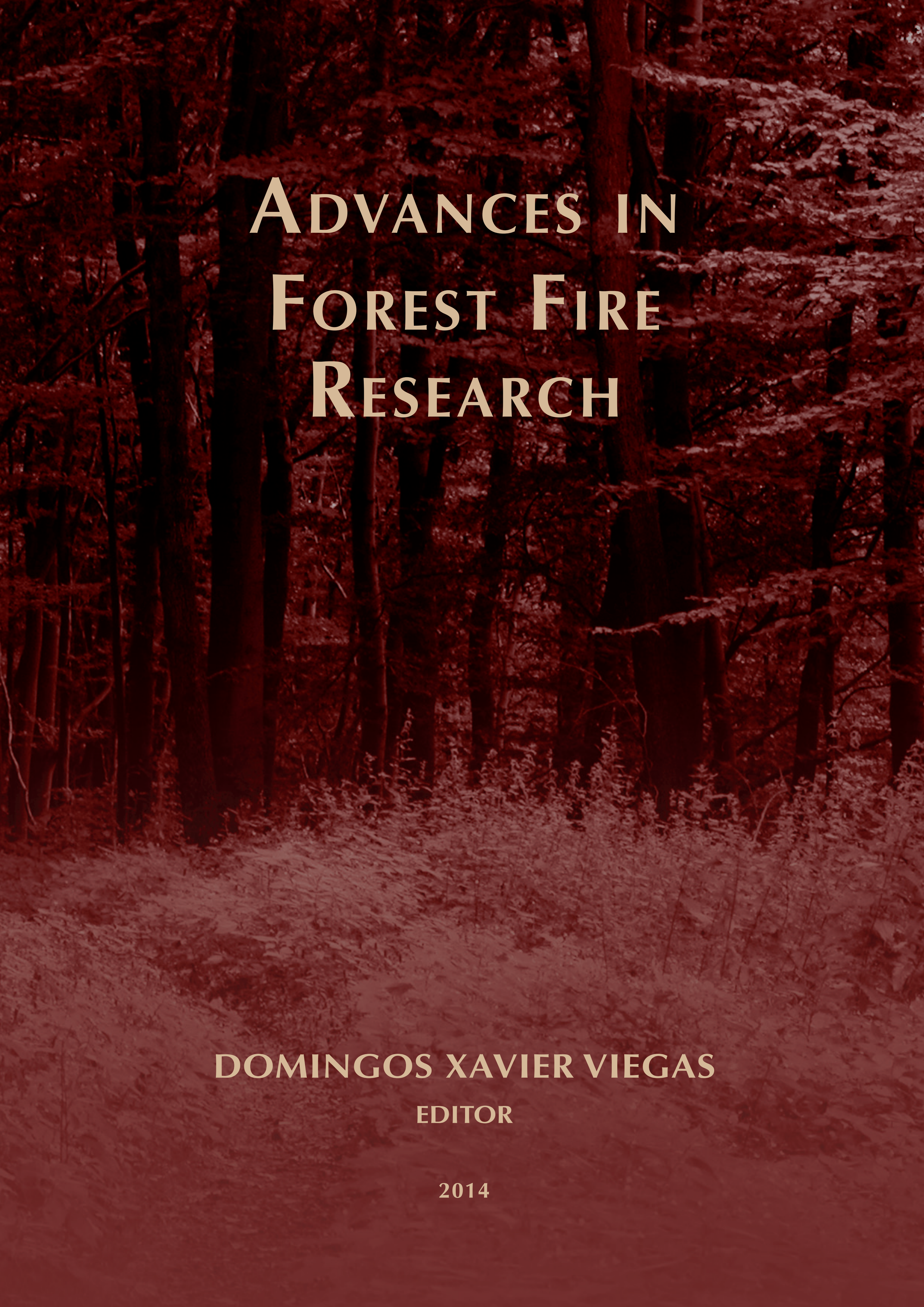

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Fine forest fuels moisture content monitoring in Central Portugal - a long term experiment

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Abstract

Forest fuel moisture content is a fundamental parameter in forest fire research and management. Due to the complexity of fuel moisture content modelling, direct field measurement is a necessary step to establish a monitoring program for fire risk applications or to assess the validity of existing models applied to different environmental conditions.
In the present study partial results from a long-term program with direct field measurements performed in Central Portugal were used to improve the knowledge on fine forest fuel moisture content.
The objective of this study is to describe seasonal and spatial patterns of the moisture content and to analyse the relation between the moisture content of the studied species.
In terms of seasonal variation, it was found that dead tree species foliage moisture content behaves in a similar way during the year. and that the average live foliage moisture content of these species is nearly constant during the year. For the shrub species, in the period between August to September, fuel moisture content decreases till its minimum yearly value.
The relation between the studied species moisture content was analysed. The relation between the dead tree species and between the shrub species presented the best correlation performance.

Keywords: *Fine fuels, moisture content.*

1. Introduction

Forest fuel moisture content (FMC) is a fundamental parameter in forest fire research and management given its implication in many aspects of fire risk including ignition probability, number and extension of fires, mode of fire spread, fire line intensity, ease of extinction and mop up (e.g. Blackmarr 1972; Rothermel 1972; Van Wagner 1987; Viegas *et al.* 1992; Dimitrakopoulos and Papaioannou 2001; Chuvieco *et al.* 2004). Due to the complexity of FMC modelling, direct field measurement is a necessary step to establish a monitoring program for fire risk applications or to assess the validity of existing models applied to different environmental conditions.
In order to assess fire risk several prediction methods that give satisfactory results, such as the Canadian Forest Fire Weather Index (Van Wagner 1987), can be used. This index mimics the moisture content trends of relevant types of fuels but direct measurements of FMC guarantee more reliable data. Despite its difficulty and cost, direct measurement of FMC does not have some of the limitations of the prediction models (Viegas *et al*. 1992).
In the present study partial results from a long-term program with direct field measurements performed in Central Portugal since 1986 (Viegas *et al*. 1992; Viegas *et al*. 2001) were used to improve the knowledge on fine forest fuel moisture content. The FMC variation range of the studied species, the seasonal FMC variation, the relations between the studied species and the relations between meteorological data and FMC will be analysed for more than 15 years of the monitoring program.

2. **Methods**

In the present study, sampling was carried out in Central Portugal, near Lousã for the period between 1996 and 2012, near Silvares and near Olho Marinho for the period between 1996 and 1999. The sampling site of Silvares is distant 5.5 km from the Lousã site, the sampling site of Olho Marinho is distant 7.7 km from Lousã site (*vide* Figure 1 and Table 1).

In the present research program, the moisture content of living and dead tree foliage from *Pinus pinaster* and *Eucalyptus globulus* and living shrub foliage and extremities from *Calluna vulgaris* and *Chamaespartium tridentatum* that are very common in the forests of Central Portugal was measured by field sampling throughout the year from 1986 to present date. In this paper the available values for the period 1996-2012 were systematized and analysed.

Living tree foliage correspond to needles of *Pinus pinaster* and leaves of *Eucalyptus globulus*, as well as small branches and leaves of *Calluna vulgaris* and *Chamaespartium tridentatum*. Dead tree foliage corresponds to needles of *Pinus pinaster* and leaves of *Eucalyptus globulus* from the litter.

Samples were daily collected at Lousã during the summer months (June to September) and once or twice a week during the rest of the year (October to May), between 12:00h and 14:00h LST.

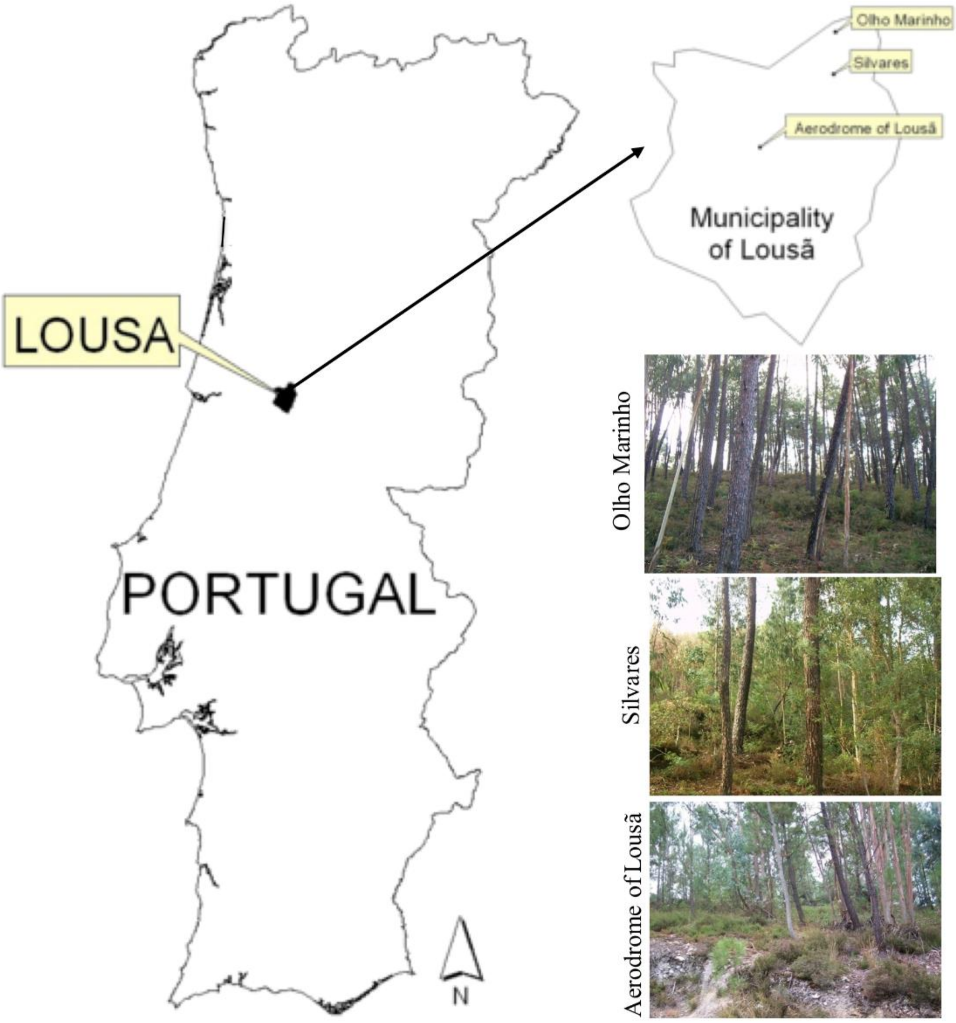

Figure 1. Geographical location of the study sites

Table 1. Main physical, climatic and vegetation characteristics of the study sites

Sampling Site	Coordinates	Altimetry (m)	Aspect	Slope (%)	Lithology	Tree height (m)	Crown closure	Vegetation
Lousã	40º8'30''N 8º14'30''W	200	South	30	Schist	10	Medium	Pinus pinaster Eucalyptus globulus Calluna vulgaris Chamaespartium tridentatum
Silvares	40º10'27''N 8º11'50''W	200	East	20	Schist	10	High	
Olho Marinho	40º11'35''N 8º11'46''W	250	East	30	Schist	10	Medium	

After the collection of approximately 50 grams of each fuel, samples were stored in a thermal bag to avoid moisture loss and immediately transported to the laboratory located in the Aerodrome of Lousã and prepared for tests. The time delay between sample collection and sample preparation was usually less than 30 minutes. If the foliage was wet with dew or rain, sampling did not occur to avoid moisture content errors.
For each fuel type, 4 samples weighing approximately 5 grams each (wet weight) were prepared and oven-dried for 24 hours at 105ºC. After the drying process, samples were weighed again in order to obtain the dry weight. The daily value of moisture content was the average of the 4 samples (*vide* Figure 2).

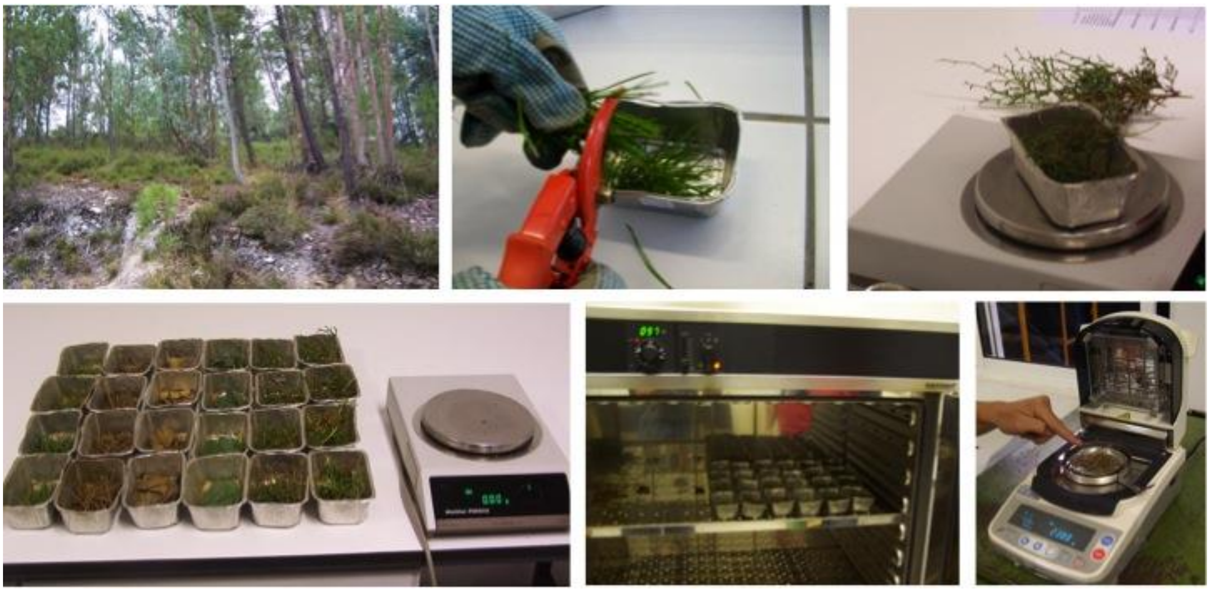

Figure 2. Sampling and determination procedures on the FMC research program of Lousã

3. **Results**

3.1. **Seasonal moisture variation of the studied species**

In Figure 3 the monthly FMC statistical parameters of the studied species for the period 1996–2012 is shown. As can be seen, for dead tree foliage from *Pinus pinaster* and *Eucalyptus globulus* values of moisture content between 2.6% and 182.9% were measured. For live tree foliage values of FMC between 68.8% and 225.3% were measured. The shrub foliage and extremities of *Calluna vulgaris* and *Chamaespartium tridentatum* presented values of FMC between 36.5% and 206.0%.

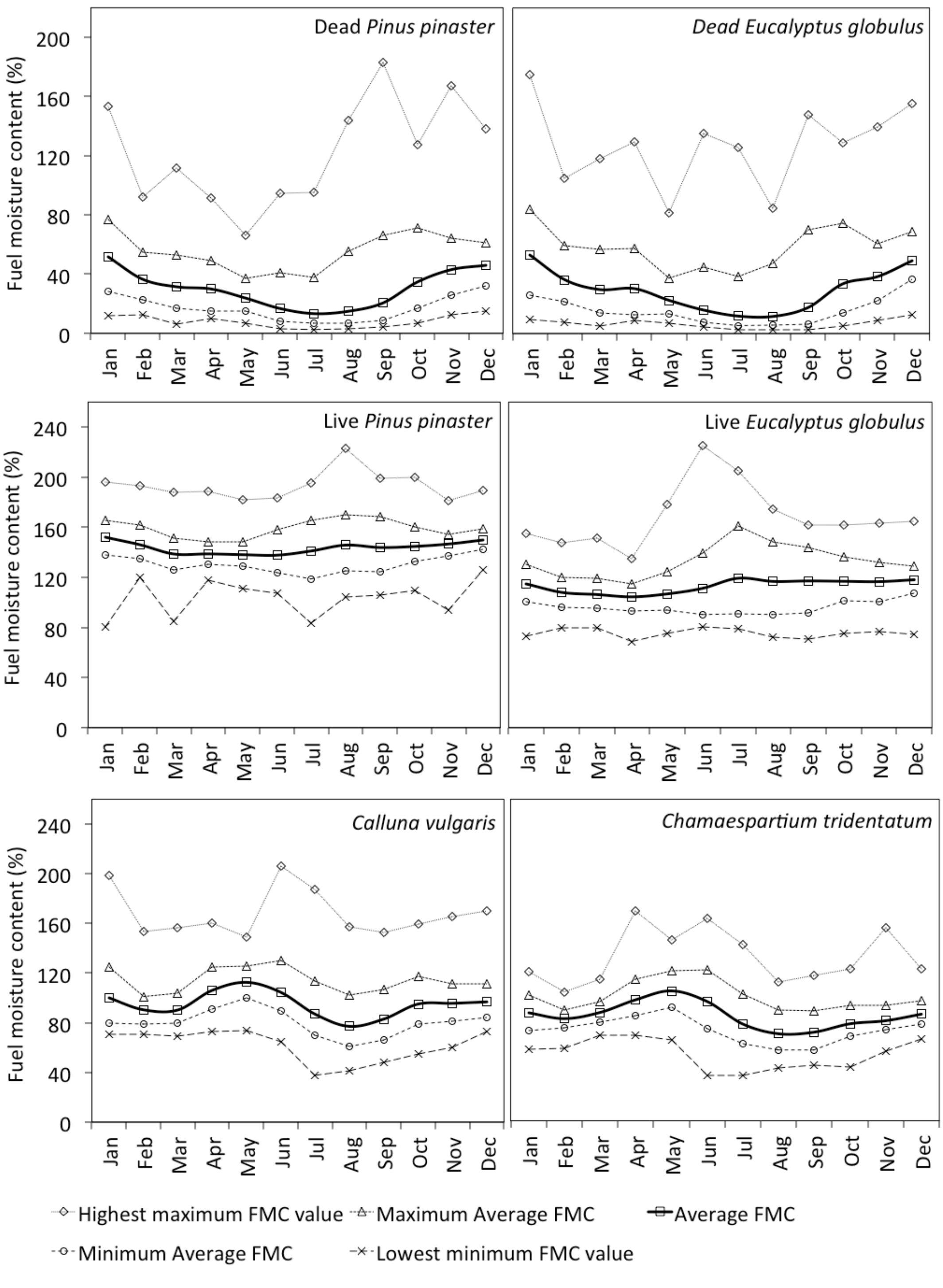

Figure 3. Monthly FMC statistical parameters of the studied species (Pinus pinaster, Eucalyptus globulus, Calluna vulgaris and Chamaespartium tridentatum) for all studied period (1996-2012)

In terms of seasonal average FMC variation, both dead tree species foliage behave in a similar way during the year. FMC is near 50% in the beginning, decreasing till a minimum of 10% in the summer months, coinciding with the forest fire period in Portugal. At the end of the year, the moisture content increases again till 50%. The average FMC of live foliage of *Pinus pinaster* is nearly constant during the year, between 140% and 150%. The same happens with live foliage of *Eucalyptus globulus* with average values of FMC between 105% and 120%. For the shrub species, in the period between August and September, FMC decreases till 80% for *Calluna vulgaris* and till 70% for *Chamaespartium tridentatum*.

3.2. Relationship between the studied species fuel moisture content

The relationship between the FMC of the studied species are analysed through the Pearson correlation coefficients presented in Table 2. Such relationship allows the estimation of the FMC of species A through the knowledge of the FMC of species B as defined in Eqn 1. In Table 3 the model parameters estimation defined in Eqn 1 are shown. This estimation was performed using linear least squares fitting based on the field measurements. As expected, the relationship between the dead tree species and the relation between the shrub species present the best performance.

Table 2. Pearson correlation coefficients between the FMC of the studied species

Relation	Dead *P. pinaster*	Live *P. pinaster*	Dead *E. globulus*	Live *E. globulus*	*C. vulgaris*	*C. tridentatum*
Dead *Pinus pinaster*	1	0.183(**)	0.909(**)	0.098(**)	0.467(**)	0.417(**)
Live *Pinus pinaster*	-	1	0.200(**)	0.090(**)	0.093(**)	0.088(**)
Dead *E. globulus*	-	-	1	0.107(**)	0.486(**)	0.443(**)
Live *E. globulus*	-	-	-	1	0.095(**)	0.051(*)
Calluna vulgaris	-	-	-	-	1	0.734(**)
C. tridentatum	-	-	-	-	-	1

(**) Significant at 0.01 level; (*) Significant at 0.05 level; (ns) Not significant

$$FMC_{Specie\ A} = aFMC_{Specie\ B} + b \tag{1}$$

Table 3. Model parameters of Eqn 1 and statistical parameters

Specie A	*Specie B*	*a*	*Std. dev.*	*b*	*Std. dev.*	*n*	R^2 *adj.*
Dead *Eucalyptus globulus*	Dead *Pinus pinaster*	1.001 (**)	0.011	-2.395 (**)	0.337	1692	0.826
Calluna vulgaris	Dead *Pinus pinaster*	0.456 (**)	0.021	79.372 (**)	0.635	1692	0.218
Chamaespartium tridentatum	Dead *Pinus pinaster*	0.330 (**)	0.017	72.554 (**)	0.528	1692	0.174
Chamaespartium tridentatum	*Calluna vulgaris*	0.594 (**)	0.013	26.695 (**)	1.223	1692	0.539

(**) Significant at 0.01 level; (*) Significant at 0.05 level; (ns) Not significant

3.3. Spatial representativity

In Viegas *et al* (1992) it was shown that dead fine FMC measurements in Lousã could be used as an indicator of fire occurrence of Central Portugal. Therefore, it is important to understand how representative the Lousã measurements are spatially in order to use this data as a fire risk indicator of a larger area.

As defined in Van Wagner (1987), the Canadian Forest Fire Weather Index (CFFWI), namely in its the sub-indexes Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC) and Drought Code (DC), the moisture content indicators of litter and other cured fine fuels in a forest stand, represent respectively, loosely compacted decomposing organic matter, and deep layer of compact organic matter. In the specific case of DC it is also an indicator of live fine FMC as shown in Viegas (2001).

Thus, for the period between 1999 and 2008, fine FMC measurements of Lousã were correlated with CFFWI moisture content sub-indexes for several weather stations in the Portuguese territory shown in the map ofFigure 4, in order to verify the existence of potential relations between the measured moisture content and CFFWI predicted moisture content and to determine the spatial representativeness of the studied species FMC.

Figure 4. Geographical location of weather stations

For this purpose, Table 4 shows the Spearman non-linear correlation coefficients between the sub-index FFMC and dead needles of Pinus Pinaster moisture content measurements and the sub-index DC and live *Chamaespartium Tridentatum* moisture content measurements.

In general terms, Table 4 and Figure 5 show that dead fine FMC measurements of Lousã can be used as a fire risk indicator with a high representativeness in the central and northeast Portuguese territory and a medium representativeness in the littoral and south regions. In terms of live fine FMC, namely for shrub species, the representativeness is, in general, medium in the central and north part of the territory and low in the rest of the territory.

Table 4. Representativeness of fine FMC measurements of Lousã in terms of the Portuguese territory

Weather Station	Dead *Pinus pinaster* / FFMC		*Chamaespartium tridentatum* / DC	
	Spearman coefficient	Representativeness	Weather Station	Spearman coefficient
Aveiro	-0,609	Medium	-0,581	Medium
Beja	-0,693	Medium	-0,535	Low
Braga	-0,721	High	-0,598	Medium
Bragança	-0,708	High	-0,557	Medium
Castelo Branco	-0,728	High	-0,540	Low
Coimbra	-0,798	High	-0,619	Medium
Évora	-0,701	High	-0,540	Low
Faro	-0,512	Low	-0,430	Low

Weather Station	Dead *Pinus pinaster* / FFMC		*Chamaespartium tridentatum* / DC	
	Spearman coefficient	Representativeness	Weather Station	Spearman coefficient
Leiria	-0,698	Medium	-0,502	Low
Lisboa	-0,710	High	-0,502	Low
Portalegre	-0,740	High	-0,586	Medium
Porto	-0,656	Medium	-0,569	Medium
Santarém	-0,706	High	-0,516	Low
Setúbal	-0,650	Medium	-0,445	Low
Viana do Castelo	-0,668	Medium	-0,580	Medium
Vila Real	-0,762	High	-0,545	Low
Viseu	-0,745	High	-0,595	Medium

High representativeness: Spearman Coefficient >0.70; Medium representativeness: 0,55< Spearman Coefficient <0.70; Low representativeness: Spearman Coefficient <0.55
All correlations are significant at the 0.01 level

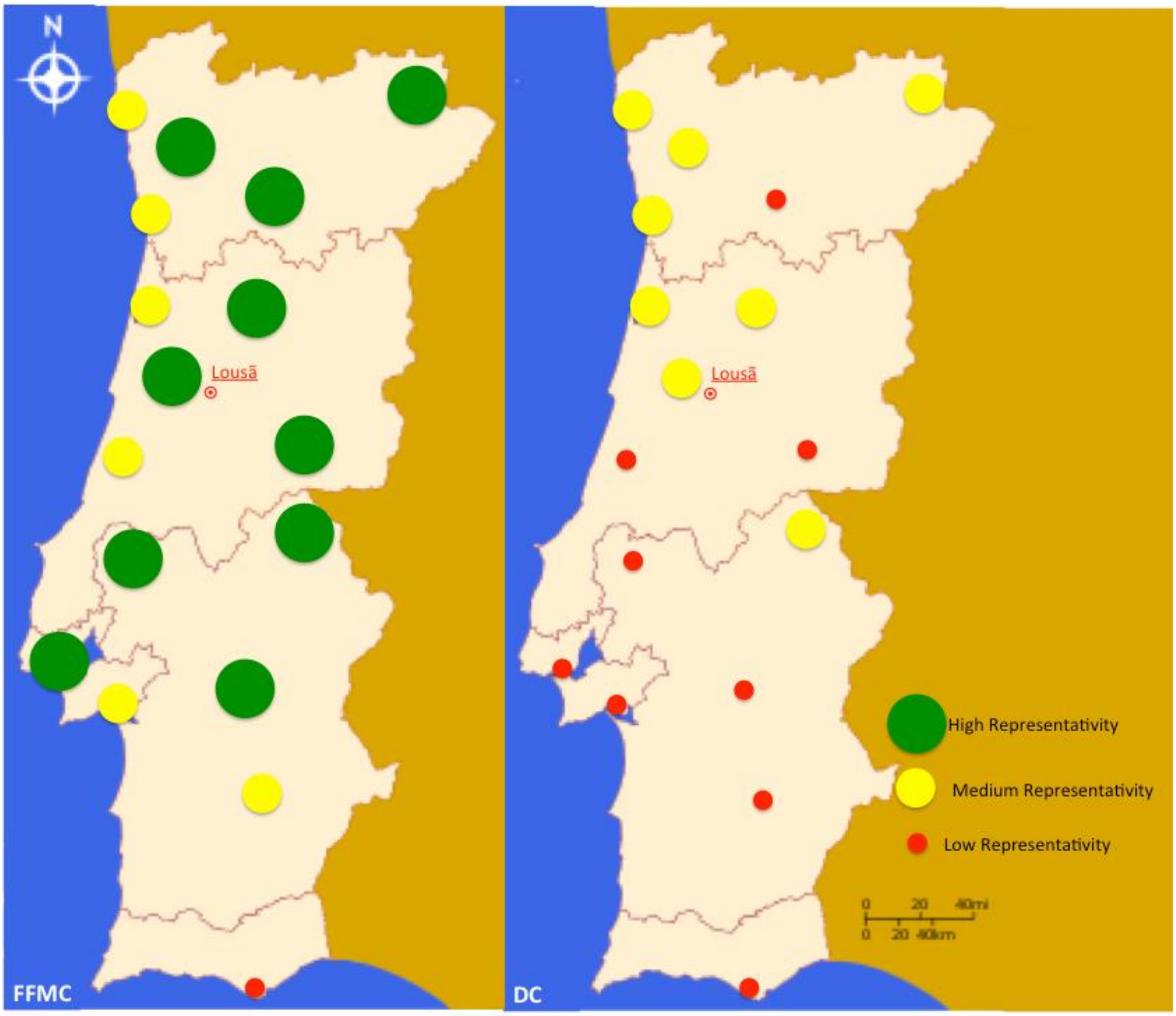

Figure 5. Representativeness of fine FMC measurements of Lousã in terms of the Portuguese territory

In order to quantify the spatial FMC patterns of the studied species (dead and live foliage of tree species, namely *Pinus pinaster* and *Eucalyptus globulus* and live shrub species, namely, *Calluna vulgaris* and *Chamaespartium tridentatum*), the data from the four sampling sites previously presented (Lousã, Silvares, Olho Marinho and Viseu) were compared. Such quantification allows the estimation of FMC of each species, in a specific location from the knowledge of the FMC of that species in a different location.

In Table 5 the Pearson correlation coefficients between the FMC for the different species measured in Lousã and in the other two sampling sites are shown. The FMC of dead foliage of the tree species (*Pinus pinaster* and *Eucalyptus globulus*) and FMC of live shrub species (*Calluna vulgaris* and *Chamaespartium tridentatum*) show good relation between the sampling site Lousã and other three sampling sites. FMC of living foliage of the tree species shows no relation.

Due to the proximity between sites, the best relations were established between Lousã and Silvares namely for dead foliage with a Pearson correlation coefficient of 0.917 for *Eucalyptus globulus* and 0.884 for *Pinus pinaster*. As expected, the relationship between FMC measured in Lousã and FMC measured in the other three sampling sites decreases as distance increases.

The linear relation between FMC of the studied specie “*A*” at the site "*X*" and the moisture content of the same species at the site "Y" for the species that show a significant Pearson correlation coefficients were calculated using a linear equation:

$$FMC_{Specie\ A\ in\ Site\ X} = a.FMC_{Specie\ A\ in\ Site\ Y} + b \qquad (1)$$

These equations were determined using the least square method. The coefficients ***a*** and ***b*** and the respective standard error, as well as the number of data (***n***) and the adjusted determination coefficient (R^2) of the obtained equations for each species are shown in Table 6.

This analysis shows that in the lack of data, it is possible to estimate the FMC of some species in a specific location from the knowledge of the FMC of that species in a different location, using linear relationships.

Table 5. Pearson correlation coefficients between the FMC values for the different species measured in Lousã and in the other three sampling sites (Silvares and Olho Marinho)

	Dead *Pinus pinaster*	Dead *Eucalyptus globulus*
Lousã and Silvares	0.884$^{(**)}$	0.917$^{(**)}$
Lousã and Olho Marinho	0.855$^{(**)}$	0.844$^{(**)}$
	Live *Pinus pinaster*	Live *Eucalyptus globulus*
Lousã and Silvares	0.092$^{(ns)}$	0.017$^{(ns)}$
Lousã and Olho Marinho	0.168$^{(**)}$	0.086$^{(ns)}$
	Calluna vulgaris	*Chamaespartium tridentatum*
Lousã and Silvares	0.654$^{(**)}$	0.676$^{(**)}$
Lousã and Olho Marinho	0.569$^{(**)}$	0.606$^{(**)}$

(**) Significant correlations at 0.01; (*) Significant correlations at 0,05; (ns) not significant

Table 6. Coefficients, a and b, number of data (n) and adjusted determination coefficient (R^2) of the obtained relation for dead tree and shrub species

Species	***Relation***	***a***	***Std. Error***	***b***	***Std. Error***	***n***	***Adjusted R^2***
Dead Pinus pinaster	Lousã (X) and Silvares (Y)	0.678$^{(**)}$	0.023	5.295$^{(**)}$	0.651	239	0.781
	Lousã (X) and Olho Marinho (Y)	0.799$^{(**)}$	0.031	3.570$^{(**)}$	0.881	239	0.730
Dead eucalyptus globulus	Lousã (X) and Silvares (Y)	0.943$^{(**)}$	0.027	1.644$^{(**)}$	0.631	239	0.841
	Lousã (X) and Olho Marinho (Y)	0.972$^{(**)}$	0.040	2.628$^{(**)}$	0.951	239	0.712
Calluna vulgaris	Lousã (X) and Silvares (Y)	0.646$^{(**)}$	0.041	27.615$^{(**)}$	3.573	329	0.426
	Lousã (X) and Olho Marinho (Y)	0.649$^{(**)}$	0.052	37.866$^{(**)}$	4.490	329	0.321
Chamaespartium tridentatum	Lousã (X) and Silvares (Y)	0.782$^{(**)}$	0.782	25.716$^{(**)}$	3.526	329	0.456
	Lousã (X) and Olho Marinho (Y)	0.682$^{(**)}$	0.050	31.458$^{(**)}$	3.705	329	0.365

(**) Significant correlations at 0.01; (*) Significant correlations at 0,05; (ns) not significant

4. Conclusion

The moisture content of forest fuels is very important in terms of forest fire research given its implication in many aspects of fire risk, fire spread and fire ecology. The long-term experience with direct field measurement in Lousã enables the study of several aspects related to fine fuel moisture content, being fundamental for fire risk applications or to assess the validity of existing or future FMC models.

In terms of seasonal variation, the litter moisture content of both tree species behaves in a similar way during the year, being close to 50% in the beginning, decreasing till a minimum of 10% during the summer months, coinciding with the forest fire period in Portugal. At the end of the year, the litter moisture content species increases again till 50%. Live *Pinus pinaster* average fuel moisture content is nearly constant during the year, between 140% and 150%. Live *Eucalyptus globulus* average fuel moisture content is also nearly constant during the year, between 105% and 120%. For the shrub species, in the period between August to September, fuel moisture content decreases till 80% for *Calluna vulgaris* and till 70% for *Chamaespartium tridentatum*.

The correlation between the studied species fuel moisture content was analysed. Such correlation allows the estimation of the fuel moisture content of one specie through the knowledge of the fuel moisture content of another specie. As expected, the relation between the dead tree species and the relation between the shrub species present the best performance. This representativeness allowed the establishment of linear relations between the FMC of a studied species at one site based on the FMC of that species in another site. This was performed between three sampling sites.

Dead fine FMC measurements of Lousã can be used as a fire risk indicator with a high representativeness in the central and northeast Portuguese territory and a medium representativeness in the littoral and south regions. In terms of live fine FMC, namely for shrub species, the representativeness is, in general, medium in the central and north part of the territory and low in the rest of the territory

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