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Fire activity in Portugal and its relationship to weather and the Canadian Fire Weather Index System

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Abstract. The relationships among the weather, the Canadian Fire Weather Index (FWI) System components, the monthly area burned, and the number of fire occurrences from 1980 to 2004 were investigated in 11 Portuguese districts that represent respectively 66% and 61% of the total area burned and number of fires in Portugal. A statistical approach was used to estimate the monthly area burned and the monthly number of fires per district, using meteorological variables and FWI System components as predictors. The approach succeeded in explaining from 60.9 to 80.4% of the variance for area burned and between 47.9 and 77.0% of the variance for the number of fires; all regressions were highly significant ($P < 0.0001$). The monthly mean and the monthly maximum of daily maximum temperatures and the monthly mean and extremes (maximum and 90th percentile) of the daily FWI were selected for all districts, except for Bragança and Porto, in the forward stepwise regression for area burned. For all districts combined, the variance explained was 80.9 and 63.0% for area burned and number of fires, respectively. Our results point to highly significant relationships among forest fires in Portugal and the weather and the Canadian FWI System. The present analysis provides baseline information for predicting the area burned and number of fires under future climate scenarios and the subsequent impacts on air quality.

Additional keywords: area burned, fire occurrence, forest fires, FWI System.

Introduction

Recently, Europe has experienced a large number of forest fires that have caused enormous losses in terms of human lives, social disturbances, environmental damage, and economic disruptions. Most of the fires in Europe take place in the Mediterranean region where over 95% of the forest fire damage occurs (EC 2003). Since 1980, the statistics for annual area burned in Portugal, Spain, France, Italy, and Greece have varied considerably from one year to the next, which can be an indication of how strongly the area burned depends on weather conditions. Fire occurrence increased during the 1990s, but since 2001, the number of fires has remained more or less stable (EC 2005). This stabilisation is possibly due to public information campaigns and improvements in the prevention and firefighting abilities of these countries.

Out of the last 25 years, 2003 was the worst fire season in Portugal, which resulted in the burning of almost 430 000 ha of forested lands and shrublands with global economic losses of 1200 million euros (DGRF 2006*a*). In that year, the social costs were most significant, with the loss of 20 human lives and the destruction of 117 houses. Owing to extreme climatic conditions, 2005 also recorded a very high area-burned figure, ~325 000 ha.

Weather and climate play a crucial role in determining the fire regime of an area (Viegas and Viegas 1994; Pyne *et al.* 1996; Skinner *et al.* 1999; Kunkel 2001; Viegas *et al.* 2001, 2004; Pereira *et al.* 2005), and so the fire regime in return is very sensitive to changes in climate (Piñol *et al.* 1998; Pausas 2004). Higher temperatures and lower relative humidity conditions generally correspond to increased area burned but not necessarily to higher fire starts.

Weather determines fuel moisture, influences lightning ignitions, and contributes to fire growth through wind action. However, the long-term average of area burned over a landscape is determined by a complex set of variables including the size of the sample area, the period under consideration, topography, fragmentation of the landscape (rivers, lakes, roads, agricultural land), fuel characteristics, season, latitude, fire suppression policies and priorities, fire control organisational size and efficiency, fire site accessibility, ignitions (people and lightning), and simultaneous fires, as well as the weather (Flannigan *et al.* 2005). Worldwide, important relationships between weather and forest fires have been established (Harrington *et al.* 1983; Flannigan and Harrington 1988; Viegas *et al.* 1992; Viegas and Viegas 1994). In Canada, weather–climate has been established as the most important natural factor influencing forest fires (Stocks and Street 1983; Flannigan and Wotton 2001; Hely *et al.* 2001).

Although some important work has been done on this topic, in southern Europe, the relationship between forest fires and weather conditions is still poorly understood. Pausas (2004) analysed the link between forest fire occurrence and climatic variables in the Valencia region of Spain and concluded that summer rainfall is an important factor for determining the amount of area burned in that region. The author also concluded that fire ignitions may be determined by human factors, but some of the variability in the annual area burned is explained by climatic

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parameters. Piñol *et al*. (1998) concluded that, in north-east Spain, a significant relationship exists between the number of very high fire risk days and the number of forest fires and area burned. Additionally, the authors noted that the number of forest fires and area burned increased from 1968 to 1994 owing to a changing climate, namely an increase in temperature and aridity. In Portugal, Viegas *et al*. (1992) and Viegas and Viegas (1994) established a clear dependency of area burned and forest fire occurrence on weather variables. Analysis of annual area burned in Portugal from 1975 to 1992 and precipitation amounts registered in Coimbra (Viegas and Viegas 1994) indicated that there is an exponential law relation ($r^2 = 0.503$) between annual area burned in Portugal and the total rainfall at the Coimbra meteorological station from May to September. The authors also concluded that the rainfall in the beginning of the fire season, namely in June, has a marked importance in the reduction of the area burned. Viegas *et al*. (2004) showed the methodology for calibrating the fire danger classes based on the statistical data of daily Fire Weather Index (FWI), number of fires, and area burned for each district of Portugal. The analysis was performed for the summer period, between June and September, from 1988 to 1996. The FWI was used as the best predictor for forest fire occurrences in each district. Owing to lack of data, some of the main meteorological stations were used for more than one district. The analysis of the number of fires, area burned, and FWI for each district showed that the range of variation of each of these parameters differs from district to district, which explains the necessity of a specific scale of risk for each parameter.

For the present study, an updated statistical analysis is performed in order to consider the most recent forest fire data that were not considered in the previous studies. In the current paper, the main objective is to perform a spatial–temporal analysis of area burned and number of fires in Portugal, at a

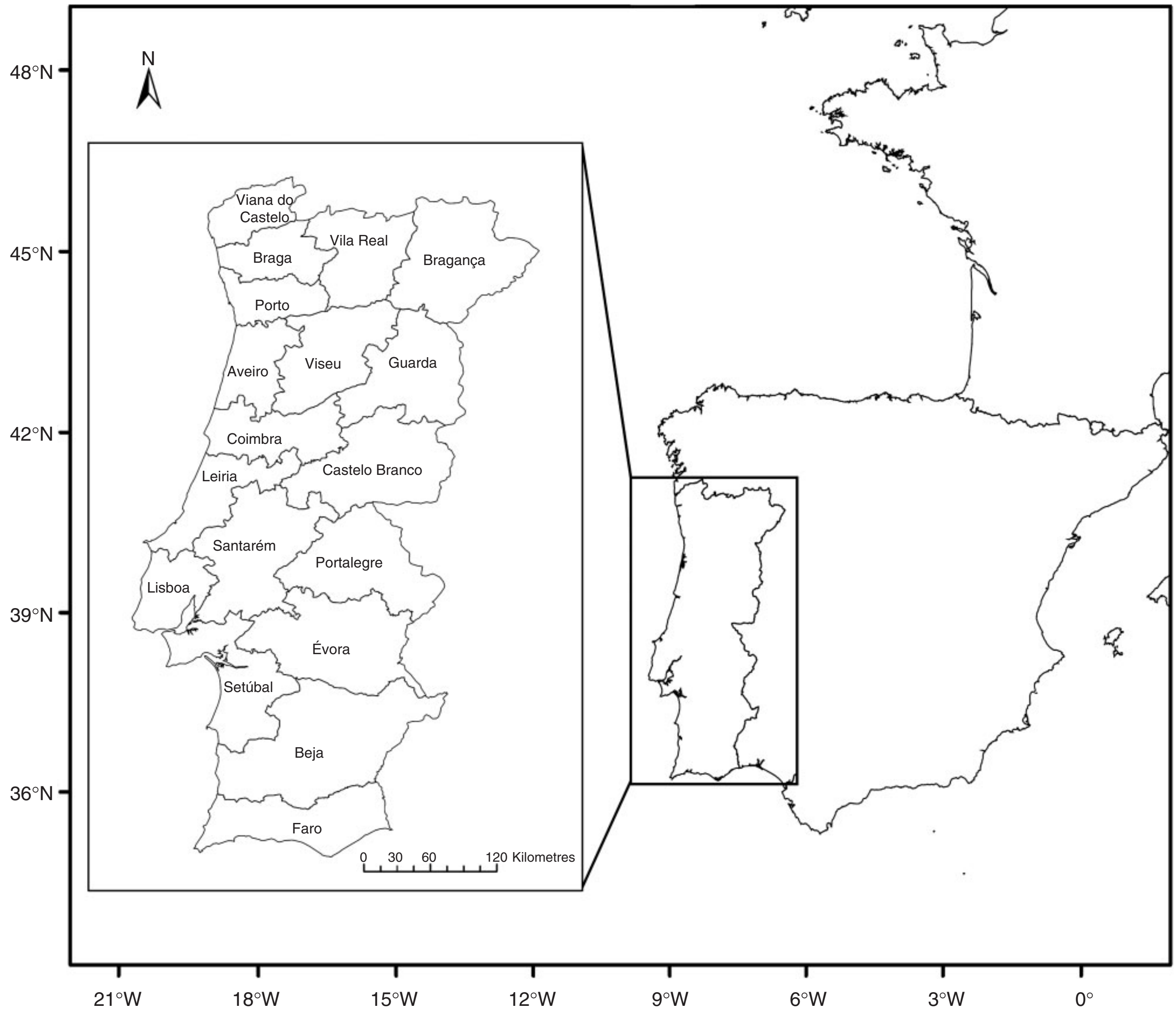

Fig. 1. Location of Portugal on the Iberian Peninsula and Portuguese districts identification.

district level, based on the historical datasets from 1980 to 2004. In a subsequent study, these relationships will be used to predict the area burned in Portugal under a future climate change scenario.

Data and methods

Study area

Forested lands in Portugal occupy 5.4 million ha and represent two-thirds of Portugal's surface area (DGRF 2006*b*). Eleven percent of the Portuguese territory is occupied by maritime pine stands or lands (*Pinus pinaster*), followed by eucalyptus (*Eucalyptus globulus*) (8%) and cork oak (*Quercus suber*) (8%). The holm oak (*Quercus rotundifolia*) represents 5%, and the oak tree (*Quercus faginea*) and stone pine (*Pinus pinea*) represent 1% each. Maritime pine is mostly represented in the Castelo Branco, Coimbra, Leiria, and Viseu districts. Aveiro, and Santarém districts have higher forest lands of eucalyptus. However, the southern districts of Évora, Portalegre, Santarém, and Setúbal have the majority of the cork oak in Portugal. The oak tree is most common in the northern districts of Vila Real, Bragança, and Guarda (Fig. 1; Table 1).

Table 1. Dominant forest types in Portugal as a percentage of district area

District name	Dominant forest type	Percentage of district area (%)
Bragança	Maritime pine	5
Vila Real	Maritime pine	17
Viana do Castelo	Maritime pine	17
Braga	Eucalyptus	16
Porto	Eucalyptus	18
Aveiro	Eucalyptus	25
Viseu	Maritime pine	23
Guarda	Maritime pine	12
Coimbra	Maritime pine	30
Castelo Branco	Maritime pine	24
Leiria	Maritime pine	30
Santarém	Cork oak	18
Portalegre	Cork oak	23
Lisboa	Eucalyptus	10
Setúbal	Cork oak	25
Évora	Holm oak	20
Beja	Holm oak	16
Faro	Cork oak	8

Some aspects of the property regime in the north and centre of Portugal, namely the high number of landowners (most of them unknown) and the absence of adequate property records, have important negative consequences concerning forest management. An increase in population inside the forested lands greatly increases the forest fire risk, enhances the destruction of goods and human lives, and creates difficulties in the firefighting operations. Land abandonment, due mainly to aging landowners, also creates difficulties in the management of forested properties, leading to an increase in the fuel load and consequently an increase in forest fire risk.

In the southern part of the country, the districts of Beja, Évora, and Portalegre have a different demographic pattern. The populations are more concentrated and not spread among the forested areas, and additionally, the dominant forest types are resistant to forest fires. These are the regions of Portugal that reach the highest temperatures during the summer period and have lower precipitation rates throughout the year. The Portuguese population is mainly concentrated in the urban and suburban areas of the coastal regions. The north region contains 35% of the population, the Lisbon area 26%, and the central part 23%. The remaining Portuguese regions represent occupation levels below 8% (INE 2003). This represents a considerable population asymmetry that certainly influences forest fire ignitions and spread.

Forest fire database

The forest fire database for Portugal used in the present study comprises the period between 1980 and 2004. The data were provided by the Direcção Geral dos Recursos Florestais (DGRF). This database constitutes the national component of the European Forest Fire Information System created by the European Commission in 1994. Regulation EEC No 804/94 (now expired) established a community system of information on forest fires for which a systematic collection of a minimum set of data on each fire occurring, the so-called 'common core', had to

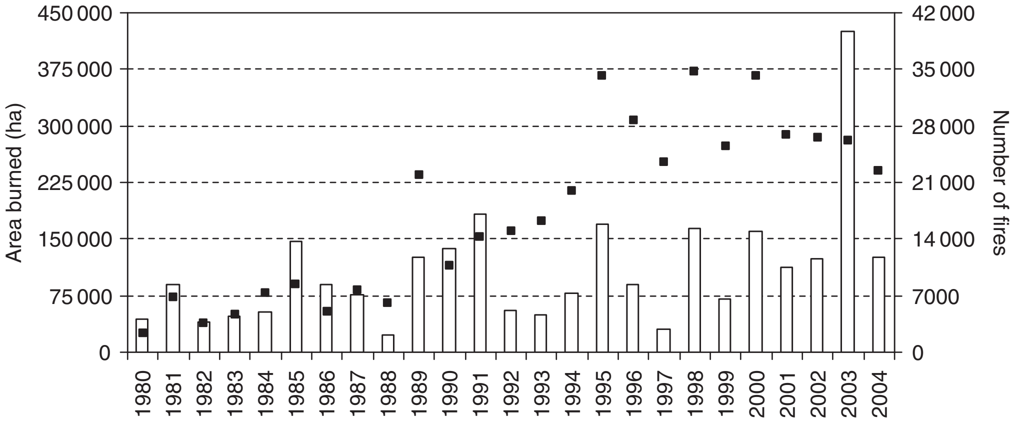

Fig. 2. Annual area burned (bars) and number of fires (square points) in Portugal for the 1980–2004 period.

be carried out by the Member States participating in the system. According to the Forest Focus Regulation (EC) No 2152/2003 currently in force concerning monitoring of forests and environment interactions in the Community, the forest fire common core data should continue to be recorded and notified in order to collect comparable information on forest fires at the Community level.

At a national level, the recorded information includes daily area burned and daily number of fires per district, among other variables. From 1980 to 2004, the dataset record comprises a total of 2.7 × 10^6 ha of area burned, ~30% of Portugal's total area, and 430 000 occurrences. The database also includes large fire information (area burned over 100 ha) concerning spatial coordinates, ignition and extinction date, vegetation type (forest,

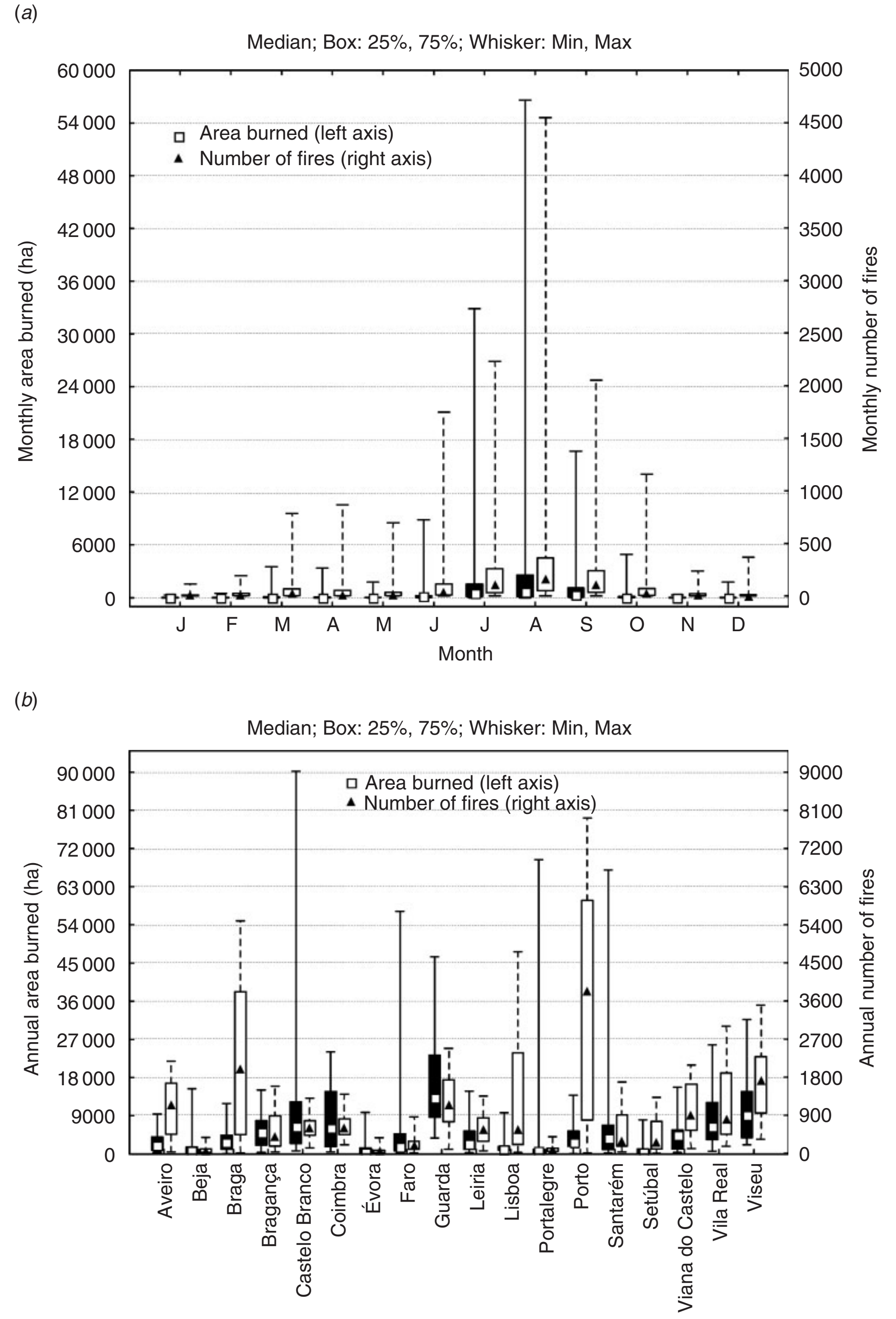

Fig. 3. Area burned and number of fires (*a*) by month, and (*b*) by Portuguese district, for the 1980–2004 period.

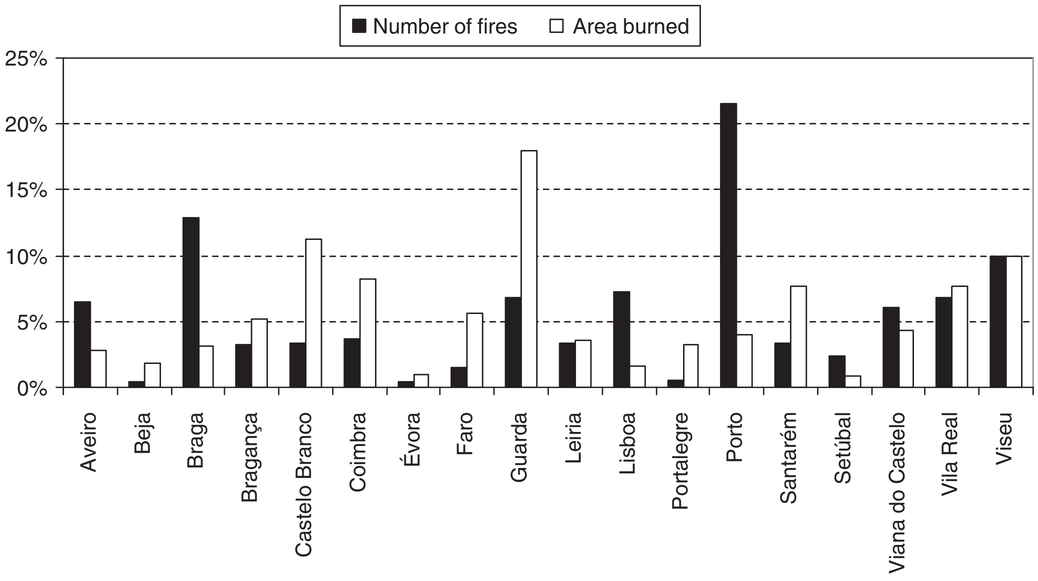

Fig. 4. Percentage of area burned and number of fires, for the 1980–2004 period per district.

Table 2. Main characteristics of the meteorological stations considered in the present study

Station name	Latitude (°N)	Longitude (°W)	Altitude (m)	Beginning date	Ending date	Number of years
Bragança	41.80	6.73	690	January 1980	December 2004	25
Vila Real	41.27	7.72	561	January 1980	December 2004	25
Porto	41.23	8.68	70	January 1980	December 2004	25
Viseu	40.67	7.90	443	May 1982	October 2004	23
Coimbra	40.15	8.47	171	January 1980	December 2004	25
Castelo Branco	39.83	7.48	386	May 1985	December 2004	19.5
Portalegre	39.28	7.42	597	January 1980	December 2004	25
Santarém	39.25	8.70	54	January 1980	December 1994	15
Lisboa	38.72	9.15	77	January 1980	December 2004	25
Évora	38.57	7.90	309	January 1980	December 2004	25
Beja	38.02	7.87	246	January 1980	December 2004	25

shrublands), and area burned. The DGRF database is based on *in situ* information provided by the Ministry of Agriculture and the National Civil Protection Service. Since 1990, annual area burned is mapped based on satellite information.

Simple statistical calculations for forest fire activity in Portugal were performed in order to better understand its main characteristics and dynamics in terms of spatial and temporal distribution.

In Portugal, the annual average area burned between 2000 and 2004 (189 671.9 ha) was 85% higher than in the 1990s (102 720.1 ha), which was already 40% higher than the 1980s annual average (73 525.4 ha) (Fig. 2). The maximum number of annual forest fires occurred in 1995, 1998, and 2000 (Fig. 2), surpassing 30 000 occurrences.

The number of fire occurrences in the months of June (8%), July (22%), August (32%), and September (20%) represent 82% of the yearly total (Fig. 3*a*). According to the National Plan for Forest Fires Prevention, the ignitions peak occurs during the weekend, and especially during the afternoon, denoting an important human influence on fire starts (APIF 2005). The districts of Guarda, Castelo Branco, Viseu, and Coimbra had the highest area burned values in Portugal (Fig. 3*b*). The area burned peak was observed in August, accounting for 45% of the yearly area burned (Fig. 3*a*).

The annual number of forest fires is significantly higher in the more urban and suburban districts (Aveiro, Braga, Lisboa, Porto, Viana do Castelo, and Setúbal) than in more rural areas (Fig. 3*b*). In terms of forest fire occurrences, the Porto district (urban–suburban region) represents the highest percentage of fire occurrences in the last 25 years, reaching almost 22% of the total. Additionally, the Guarda district (rural region) accounts for almost 18% of the area burned in Portugal, followed by Castelo Branco with 11% (Fig. 4).

From 1993 to 2003, 97% of the forest fire ignitions were due to human influence, with 37% due to arson, 28% to negligence, and 32% to unknown causes (APIF 2005). Arson is mainly related to fraud, hunting conflicts, and building construction interests, and is most notorious in the northern part of the country and especially in the coastal regions. Negligence is the most important cause in the south, mainly due to clearance activities. In contrast, in the southern districts of Beja, Évora, and Portalegre, the principal cause of negligence is related to agricultural machinery use. In the Santarém district, the main cause is related to transportation and communications activities. Specific regional patterns are also responsible for forest fires starts, such as fireworks activity in the northern districts of the country (APIF 2005). Portugal, as in the majority of the Mediterranean countries, has fewer forest fires due to natural causes because phenomena such as lightning have a low frequency of occurrence during the summer period.

Meteorological data

Data for daily maximum temperature, daily mean temperature, relative humidity, wind speed, and total rainfall from 1980 to 2004 were compiled. Eleven stations were analysed over Portugal, covering the majority of the country except the Algarve region (southern district) and the north-west region for which we did not have available data. Table 2 presents the stations analysed and their principal characteristics.

Some of the studied stations were lacking data covering the full period under analysis (Santarém, Castelo Branco, and Viseu). From 1980 until the end of 2004, Viseu station only contained data from May to October.

The majority of the meteorological data came from the Portuguese Meteorological Institute (maximum temperature, dry bulb temperature, wet bulb temperature, rainfall, and wind speed). Some stations were missing data for short periods and these were filled using the National Climatic Data Centre (NCDC) database (NCDC 2006).

Fire Weather Index (FWI) System

The 1200 Local Standard Time (LST) observations of temperature, relative humidity, wind speed, and 24-h precipitation are the inputs required to calculate the components of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987). The FWI System is a weather-based system that models fuel moisture using a dynamic bookkeeping system that tracks the drying and wetting of distinct fuel layers in the forest floor. There are three moisture codes that represent the moisture content of fine fuels (fine fuel moisture code, FFMC), loosely compacted organic material (duff moisture code, DMC), and a deep layer of compact organic material (drought code, DC). The drying timelags for these three fuel layers are 2/3 of a day, 15 days, and 52 days, respectively, for the FFMC, DMC, and DC under normal conditions (temperature 21.1°C, relative humidity 45%). These moisture indexes are combined to create a generalised index of the availability of fuel for consumption (build-up index, BUI). The FFMC is combined with wind speed to estimate the potential spread rate of a fire (initial spread index, ISI). The BUI and ISI are combined to create the FWI, which is an estimate of the potential intensity of a spreading fire. The daily severity rating (DSR) is a simple power function of the FWI intended to increase the weight of higher values of FWI in order to compensate for the exponential increase in area burned with fire diameter (Williams 1959; Van Wagner 1970). Viegas *et al.* (1999) pointed out that the FWI System is one of the most adequate fire risk assessment tools for Mediterranean countries, especially Portugal. The FWI System is applied nowadays by the national authorities to forecast the fire danger over Portugal.

Table 3. Meteorological and Fire Weather Index (FWI) System variables

FFMC	Mean fine fuel moisture code
FFMCX	Maximum fine fuel moisture code
FFMCP90	90th percentile of fine fuel moisture code
DC	Mean drought code
DCX	Maximum drought code
DCP90	90th percentile drought code
DMC	Mean duff moisture code
DMCX	Maximum duff moisture code
DMCP90	90th percentile duff moisture code
BUI	Mean build-up index
BUIX	Maximum build-up index
BUIP90	90th percentile build-up index
ISI	Mean initial spread index
ISIX	Maximum initial spread index
ISIP90	90th percentile initial spread index
FWI	Mean fire weather index
FWIX	Maximum fire weather index
FWIP90	90th percentile fire weather index
DSR	Mean daily severity ratio
DSRX	Maximum daily severity ratio
DSRP90	90th percentile daily severity ratio
TX	Mean of maximum daily temperatures (°C)
TXX	Maximum of maximum daily temperatures (°C)
TXP90	90th percentile of maximum daily temperatures (°C)
RH	Mean relative humidity (%)
TPREC	Total precipitation (mm)

For the purposes of the present study, the FWI System components were computed using daily mean values of temperature, relative humidity, wind speed, and daily total precipitation. In order to evaluate the relationship between daily mean and noon values, the FWI index was computed at 1200 LST and on a daily average basis for Coimbra and Portalegre stations (stations for which we had noon weather data). Both stations presented a Pearson coefficient above 0.93 ($P < 0.0001$). Coimbra and Portalegre presented a negative bias between the daily mean FWI and the noon FWI of -3.5 and -2.4, respectively, indicating a slight underestimation. Based on these relationships, we determined that the mean daily values were suitable for use in the present study.

Statistical Analysis System (*SAS*) version 9.1.3 (SAS Institude Inc. 2004) was used for the FWI System components' estimation and for all the statistical analyses carried out. All the analyses were performed at a significance level of 0.05. Means and extremes of the meteorological variables and the FWI System components were calculated for daily, monthly, and seasonal (1 May to 31 October) periods. Extremes of the variables (maximum and 90th percentile) were also calculated because much of the area burned occurs during extreme fire weather conditions.

The natural logarithm of the area burned (ha) and the natural logarithm of the number of fires were used to normalise, respectively, the area burned and the number of fires, because the raw data distribution is non-normal. A unit was added to the observed area burned and number of fires in order to avoid the zero values in the logarithmic calculation. A correlation matrix was constructed for each district and for each period (seasonal, monthly, and daily) with the natural logarithm of area burned and the natural logarithm of the number of fires considering the variables listed in Table 3. All variables listed in Table 3 were then introduced in the forward stepwise regression and the terms were accepted only if they met the 0.05 significance level.

Results and discussion

The correlation procedure established that the best results were obtained on a monthly basis compared with daily and seasonal periods (not shown). Tables 4 and 5 present the results from the forward stepwise regression of monthly area burned and monthly number of fires for 11 districts across Portugal. All of the variables listed in Table 3 were available for the stepwise regression and only the significant terms were kept. The selected significant variables are arranged by order of importance. The analysed districts shown in Tables 4 and 5 are organised from north to south. The DC, BUI, DMC, FWI, DSR, and FFMC components, and the maximum temperature and relative humidity, means and extremes were the selected significant variables from the stepwise regression, depending on the district. Mean or maximum temperature was selected by all districts in the north and central regions except Vila Real and Santarém. For the southern districts of Évora and Beja, only the FWI index was selected as the best predictor for area burned. The FWI was also selected by almost all the districts except Bragança and Porto. For the number of fires, the mean and maximum temperature was the first order selection by almost all districts except Portalegre, Santarém, and Évora.

The variance explained ranges from 43.1 to 80.4% for area burned and 36.5 to 77.0% for number of fires, depending on district, and all regressions were highly significant ($P < 0.0001$). The monthly mean and the monthly maximum of daily maximum

Table 4. District monthly area burned explained variance (r^2) and variables selected, in order of importance, by stepwise regression

See Table 3 for definition of variables

District	Significant variables	Explained variance (%)	*n*	*P*
Bragança	TX, DC, BUI	63.3	300	<0.0001
Vila Real	FWIP90, FFMC, DC, RH	67.9	300	<0.0001
Porto	DMCX, TXX, FFMC	65.4	300	<0.0001
Viseu	DCX, FFMC, FWIX, TXX	80.4	138	<0.0001
Coimbra	FWI, TXX, DC	72.6	300	<0.0001
Castelo Branco	FWIP90, BUI, TX	75.6	236	<0.0001
Portalegre	FWI, TXX	45.6	300	<0.0001
Santarém	FWI, DSRX	78.5	180	<0.0001
Lisboa	TXX, DC, FWI	68.4	300	<0.0001
Évora	FWI	43.1	300	<0.0001
Beja	FWIP90	57.8	300	<0.0001
Portalegre, Évora, Beja	FWIP90, TX	60.9	300	<0.0001
All districts	FWIX, RH, DC	80.9	300	<0.0001

Table 5. District monthly number of fires explained variance (r^2) and variables selected, in order of importance, by stepwise regression

See Table 3 for definition of variables

District	Significant variables	Explained variance (%)	*n*	*P*
Bragança	TX, DC	53.3	300	<0.0001
Vila Real	BUIP90, FFMCX, DC, RH	58.3	300	<0.0001
Porto	TXX, RH, DMCX	56.9	300	<0.0001
Viseu	TXX, DCX, FWIX	71.8	138	<0.0001
Coimbra	TXX, FFMC, BUIP90	69.1	300	<0.0001
Castelo Branco	TX, FFMC, BUI	67.7	236	<0.0001
Portalegre	RH, DCX	39.8	300	<0.0001
Santarém	FWI, DCX, FWIP90	77.0	180	<0.0001
Lisboa	TXX, DC	49.1	300	<0.0001
Évora	FWIX, RH	36.5	300	<0.0001
Beja	TX, FWIX	44.5	300	<0.0001
Portalegre, Évora, Beja	TXX, RH, DC	47.9	300	<0.0001
All districts	TXP90, FWIP90, FFMCX	63.0	300	<0.0001

temperatures (TX) and the monthly mean and extremes (maximum and 90th percentile) of the FWI were selected by all the stations except Bragança and Porto. The districts under evaluation in the north and central regions accounted for 48% in terms of the total area burned and 56% for the number of fires in the 1980–2004 period. In the districts of Santarém, Évora, Beja, and Portalegre, the area burned accounted for 17.7% of the total, and the number of fires accounted for 4.8% of the total. The FWI and the temperature were the best predictors for the area burned in these districts.

According to Tables 4 and 5, the significant variables that explained the majority of the variance in both area burned and number of fires definitely differ, although most of the significant variables could be found in all districts and in both regressions except Portalegre. The results achieved point to an interesting north–centre *v.* south dichotomy in terms of fire weather. The southern districts selected fewer significant variables in their regression models. These findings can be supported by the different local physical conditions that explain this behaviour. The type of forest and shrubland, in addition to the population distribution, can also explain the forest fire behaviour in the different Portuguese regions. All districts in north and central regions exhibited variances above 60% and above 50% for area burned and number of fires, respectively. The highest correlation was found in the Viseu district, reaching 80.4%, but the number of values used in the regression model was the lowest among all analysed districts when only considering the summer months from May to October. The highest explained variance for the number of fires was in the Santarém district, reaching 77%, but this district has meteorological data for only 15 years (Table 2).

Portalegre, Évora, and Beja districts had lower explained variance values and also had the lowest values of area burned and

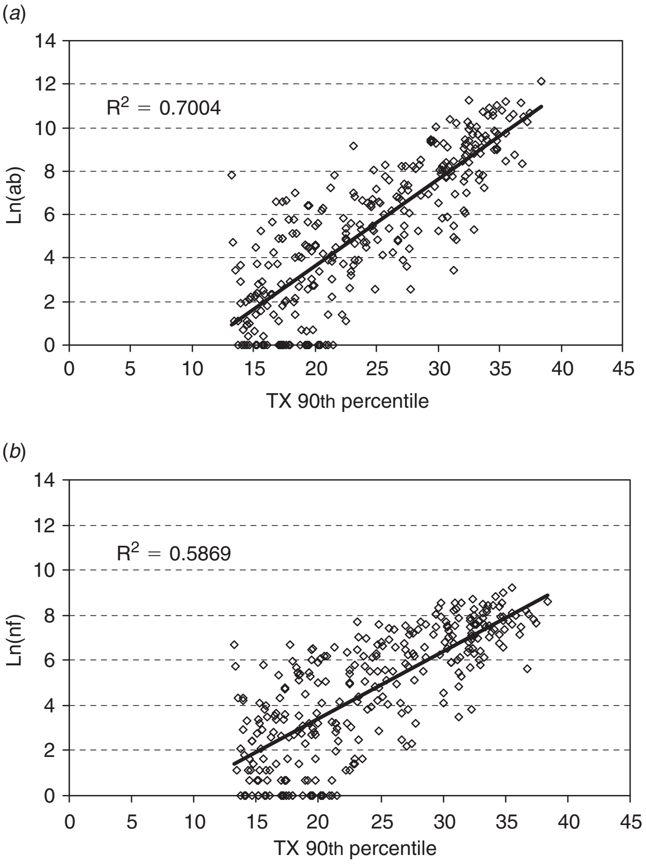

Fig. 5. Natural logarithm of the (*a*) monthly area burned, and (*b*) monthly number of fires *v.* monthly 90th percentile of daily maximum temperature in Portugal, for the 1980–2004 period.

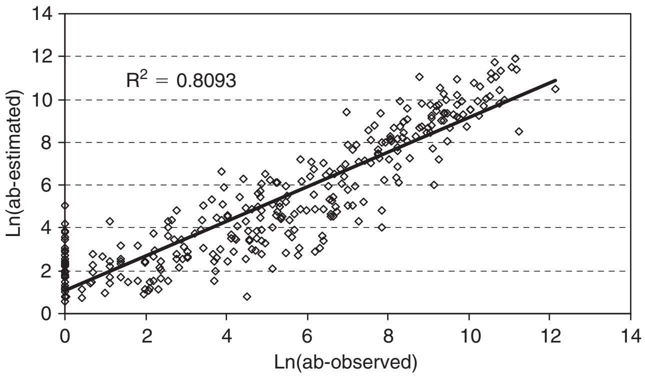

Fig. 6. Natural logarithm of the estimated monthly area burned *v.* the natural logarithm of the observed monthly area burned, for the 1980–2004 period.

Table 6. Regression model selected by stepwise regression for natural logarithm of monthly area burned (TX and TXX in °C)

See Table 3 for definition of variables

District	Regression model ln(ab)	*P*
Bragança	$-1.803 + 0.206\mathrm{TX} + 000232\mathrm{DC} + 0.0104\mathrm{BUI}$	<0.0001
Vila Real	$5.140 - 0.0678\mathrm{RH} + 0.0274\mathrm{FFMC} + 0.00379\mathrm{DC} + 0.0956\mathrm{FWIP90}$	<0.0001
Porto	$-4.589 + 0.0357\mathrm{FFMC} + 0.161\mathrm{TXX} + 0.0466\mathrm{DMCX}$	<0.0001
Viseu	$-4.021 + 0.0412\mathrm{FFMC} + 0.111\mathrm{TXX} + 0.00547\mathrm{DCX} + 0.0506\mathrm{FWIX}$	<0.0001
Coimbra	$-1.824 + 0.00221\mathrm{DC} + 0.301\mathrm{FWI} + 0.102\mathrm{TXX}$	<0.0001
Castelo Branco	$-1.164 + 0.124\mathrm{TX} + 0.00921\mathrm{BUI} + 0.0749\mathrm{FWIP90}$	<0.0001
Santarém	$0.161 + 0.209\mathrm{FWI} + 0.174\mathrm{DSRX}$	<0.0001
Lisboa	$-2.700 + 0.00242\mathrm{DC} + 0.0623\mathrm{FWI} + 0.145\mathrm{TXX}$	<0.0001
Portalegre, Évora, Beja	$-1.329 + 0.103\mathrm{TX} + 0.0882\mathrm{FWIP90}$	<0.0001
All districts	$15.007 - 0.131\mathrm{RH} + 0.00308\mathrm{DC} + 0.0813\mathrm{FWIX}$	<0.0001

number of fires. In these districts, the temperatures can reach very high values (up to 40°C), associated with low relative humidity, but the fuel characteristics and the physical conditions are different from the rest of the country. The typical forest species in this part of the country (cork oak and holm oak) are resistant to fire. In this context, it seemed appropriate to group these three districts. According to this new analysis, the monthly mean of TX and the FWI 90th percentile explained 60.9% of area burned, whereas the monthly means of DC, relative humidity (RH), and the monthly maximum of daily maximum temperature (TXX) explained 47.9% of the number of fires (Tables 4 and 5). This group analysis significantly improved the variance explained in area burned and number of fires in this part of the country.

For the average Portuguese meteorological conditions based on the data from 11 districts, the best predictors for the natural logarithm of area burned were the DC, RH, and the maximum FWI, explaining 80.9% of the variance in area burned. The best predictors for the monthly number of fires were the TX 90th percentile, the FWI 90th percentile, and the maximum FFMC (FFMCX), which explained 63.0% of the variance (Tables 4 and 5). The maximum and 90th percentile of the FWI component were selected by both regression models. Fig. 5 presents the relationship between the natural logarithm of monthly area burned and the natural logarithm of monthly number of fires *v.* the monthly 90th percentile of daily maximum temperature for Portugal, where temperature alone explained 70% of the variance in the area burned and 59% in the number of fires. The temperature was not selected in the regression model, but by itself, it exhibited a very good correlation with area burned in Portugal. Fig. 5 demonstrates that the relationships were linear for the natural logarithm of area burned and the natural logarithm of the number of fires and were representative of all analysed stations. In Fig. 5, there are some data points with zero area burned and zero number of fires despite high 90th percentile temperatures; this may be related to the lack of ignitions in those months. It is obvious that very severe fire weather notwithstanding, there will be no area burned without an ignition and this might explain part of some of the unexplained variance in the regressions (Flannigan *et al.* 2005).

Using the regression equation for average Portuguese conditions from Table 6, we estimated the monthly area burned and plotted it against the observed area burned (Fig. 6). We noted that there is a general trend to underestimate the monthly area burned in Portugal using the regression equation obtained. This underestimation is likely due to factors other than the weather

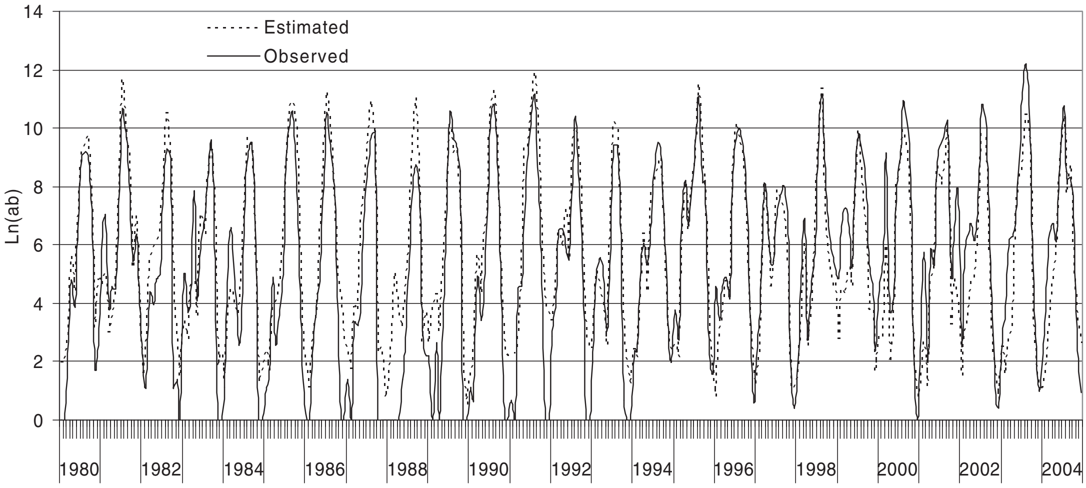

Fig. 7. Natural logarithm of the observed and estimated monthly area burned between 1980 and 2004, over Portugal.

Table 7. Regression model selected by stepwise regression for natural logarithm of monthly number of fires (TX and TXX in °C)
See Table 3 for definition of variables

District	Regression model ln(nf)	*P*
Bragança	$-1.223 + 0.156\mathrm{TX} + 0.00205\mathrm{DC}$	<0.0001
Vila Real	$3.638 - 0.0712\mathrm{RH} + 0.00239\mathrm{DC} + 0.0402\mathrm{FFMCX} + 0.00864\mathrm{BUIP90}$	<0.0001
Porto	$4.273 - 0.0919\mathrm{RH} + 0.203\mathrm{TX} + 0.0347\mathrm{DMCX}$	<0.0001
Viseu	$-2.157 + 0.141\mathrm{TXX} + 0.00383\mathrm{DCX} + 0.0406\mathrm{FWIX}$	<0.0001
Coimbra	$-2.840 + 0.0352\mathrm{FFMC} + 0.0826\mathrm{TXX} + 0.0154\mathrm{BUIP90}$	<0.0001
Castelo Branco	$-2.153 + 0.126\mathrm{TX} + 0.0240\mathrm{FFMC} + 0.00621\mathrm{BUI}$	<0.0001
Santarém	$0.0443 + 0.0987\mathrm{FWI} + 0.0525\mathrm{FWIP90} + 0.000585\mathrm{DCX}$	<0.0001
Lisboa	$-3.004 + 0.00466\mathrm{DC} + 0.189\mathrm{TXX}$	<0.0001
Portalegre, Évora, Beja	$2.751 - 0.0436\mathrm{RH} + 0.000950\mathrm{DC} + 0.0591\mathrm{TXX}$	<0.0001
All districts	$-7.675 + 0.100\mathrm{FFMCX} + 0.116\mathrm{TXP90} + 0.0958\mathrm{FWIP90}$	<0.0001

and the FWI components that are responsible for the unexplained variance in the area burned data.

Fig. 7 shows a more detailed analysis of the relationship between the estimated and the observed monthly area burned in Portugal for the 1980–2004 period. According to Fig. 7, from 1980 to 1993, there is a trend to overestimate the maximum and minimum values of the monthly area burned. Since 2000, the area burned over Portugal is underestimated. The analysis of Figs 6 and 7 indicates that the underestimation of the area burned in the last years of the analysis is stronger than the overestimation for the period between 1980 and 2003, leading to an overall underestimation of the area burned by the statistical model developed. As stated in the *Forest fire database* section, the period between 2000 and 2004 had the highest average annual area burned of the overall analysed period, contributing to the enhancement of the differences between observed and simulated values.

Tables 6 and 7 present the regression models obtained for each analysed district and for the average conditions over Portugal. All the terms were significant at a 0.05 level. The regression models obtained constituted the best tool to diagnose the area burned and forest fire occurrence in Portugal.

Concerning the statistics obtained, each district has different fuel distributions with particular characteristics that may also explain some of the variance in the area burned and number of fires. The way the different districts deal with forest fire prevention and firefighting is another reason for the unexplained variance. The prevention campaigns that each local authority implements are another aspect that influences the forest fires statistics. It should be noted that the fuel characteristics were not explicitly treated, but implicitly, their expression is detected in fire statistics. An important source of uncertainty is related to the meteorological data acquisition and forest fire data records. After 1992, the area burned data records are more precise. In the current paper, the Guarda district, an important Portuguese district in terms of area burned (18% of total area burned in Portugal), was not considered owing to lack of meteorological data for the 1980–2004 period.

Conclusions

The present work investigated the relationship between the weather, the FWI System components, and both the area burned and fire occurrences in 11 Portuguese districts. Results suggest that fire weather explains the majority of the variance of the area burned and the number of fires in Portugal. The DC, BUI, DMC, FWI, DSR, and FFMC components, along with the means and extremes of temperature and relative humidity, were the selected significant variables by stepwise regression, depending on the district. For the average conditions of the 11 Portuguese districts under analysis, almost 81% of the variance in area burned was explained by the monthly mean of RH and DC and by the monthly maximum FWI. The explained variance for number of fires reached 63%. Among the districts, the explained variance ranged from 60.9 to 80.4% and 47.9 to 77.0% for area burned and number of fires, respectively.

In subsequent studies, the current work will serve as baseline information to predict the magnitude of area burned in Portugal under future climatic scenarios and to evaluate its potential impacts, namely on forest fire emissions and consequently on air quality and human health.

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