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ORIGINAL ARTICLE

Sensitivity of Portuguese forest fires to climatic, human, and landscape variables: subnational differences between fire drivers in extreme fire years and decadal averages

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Abstract Within the changing fire regimes of Portugal, the relative importance of humans and climatic variability for regional fire statistics remains poorly understood. This work investigates the statistical relationship between temporal dynamics of fire events in Portugal and a set of socioeconomic, landscape, and climatic variables for the time periods of 1980–1990, 1991–2000, and extreme fires years. For 10 of 15 districts, it was possible to observe moderate shifts in the significance of fire drivers for the first two decadal periods. For others, pronounced changes of the significance of fire drivers were found across time. Results point toward a dynamic (perhaps highly non-linear) behavior of socioeconomic and landscape fire drivers, especially during the occurrence of extreme fire years of 2003 and 2005. At country level, population density alone explained 42% of the inter-annual and inter-district deviance in number of fires. At the same temporal and spatial scale, the explanatory power of temperature anomalies proved to explain 43% of area burnt. We highlight the necessity of including a broad set of socioeconomic and landscape fire drivers in order to account for potential significance shifts. In addition, although climate does trigger broad favorable fire conditions across Portugal mainland, socioeconomic and landscape factors proved to determine much of the complex fire patterns at a subnational scale.

Keywords Wildfires · Portugal · Fire drivers · Socioeconomic · Climate

Introduction

Despite a common generalization that greater fire frequencies are noted in the Mediterranean regions of Europe (Pausas 2004), fire statistics of individual Mediterranean countries show a more heterogeneous regional and temporal development regarding fire occurrences (Bassi et al. 2008). In Portugal, although changes in fire regimes were noted over the past two decades (Pereira et al. 2005), the relative importance of humans and climatic variability on regional fire statistics remains poorly understood (Carvalho et al. 2008). In this context, determining the spatial and temporal distribution of fire drivers in Portugal at a subnational scale could provide further clarification on the forces driving the changes in Mediterranean fire regimes.

Regional patterns of forest fires depend on numerous human, landscape, and climatic factors that change frequently in time and space (Cueva 2006). In Portugal, socioeconomic development during the last decades has lead to the migration of rural population to urban centers contributing to a high landscape-level susceptibility to fire (Pereira et al. 2005). With more people leaving rural areas, an increase in fuel load was observed, most likely due to natural conversion of agricultural land and a reduction in the consumption of fuels by animal grazing and fuel wood harvesting (Rego 1992; Pausas 2004). Climatic factors are also known to influence both fire risk and fire propagation (Dube 2009). In Portugal, climate analysis shows a general

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trend toward an increase in mean annual surface air temperature from 1972 until 2000 (Santos et al. 2002). In respect to precipitation, although changes in the annual mean are not evident, a systematic reduction in spring precipitation in all stations of the Portuguese mainland was observed for the period 1931–2000 (Santos et al. 2002). Future climate change scenarios reveal a consistent picture of substantial warming and precipitation reduction in south Mediterranean regions (Giorgio and Lionello 2007). In the warm season, precipitation decreases may exceed 20–30% and warming exceed 4–5°C by 2100 (Giorgio and Lionello 2007). Further effect of climate change on changing fire regimes is not yet fully understood (Flannigan et al. 2000; Dube 2009). A climatic shift toward more frequent dry periods and seasonal precipitation shifts in the Mediterranean (Giorgio and Lionello 2007) is expected to interact with socioeconomic and landscape factors in determining the number of fires (Filipe et al. 2009).

The probability of extreme climatic events adds further uncertainty to both the extent and consequences of future forest fire events. For example, during the 2003 heat wave, a record number of large wildfires were observed in European countries (Barbosa et al. 2003). In Portugal, area burnt was more than twice the previous extreme (1998) and four times the 1980–2004 average (Trigo et al. 2006). As a result, 8.6% of the Portuguese total forest area was burned leading to an economic impact exceeding 1billion € (De Bono et al. 2004). More recently, the unusual extent of the 2007 Greek forest fires exposed the vulnerabilities of fire defense mechanisms when multiple ignition patterns and favorable climatic conditions occur simultaneously (Xanthopoulos 2007). The impact of forest fire goes beyond the social and economic spheres. Fires are regarded as one of the main threats for Mediterranean biodiversity (WWF 2003). In Portugal, 45% of mammals, birds, amphibians, and reptiles are associated with forests, particularly with deciduous and evergreen oak forest (Pereira et al. 2005). Though comprising many species adapted to cope with recurrent fires, Mediterranean vegetation has only a limited capacity to cope with fire (Kazanis and Arianoutsou 2002). Variation in fire regime related to increasing fire recurrence, intensity, or timing may result in vegetation changes (Lloret et al. 2003), in addition, fire frequencies above long-term averages are believed to cause a reduction in ecosystems resilience (Díaz-Delgado et al. 2002).

Due to the potential large impact of forest fires and the uncertainty of climate change effects in future extreme fire events, contemporary and past relations between fire drivers and fire statistics at a subnational scale are addressed in this study. We analyze which variables (anthropogenic, landscape, or climatic) determine the inter-annual occurrence and extension of Portuguese forest fires at national and individual district level. At district level, not only we investigate the importance of selected variable in describing fire events but also we investigate whether their significance remains constant or whether changes in particularly severe fire years can be observed. Finally, we evaluate the influence that climate exerts on the occurrence and spatial pattern of fire in comparison with socioeconomic and landscape factors.

Methods

Selected variables

Portuguese fire statistics regarding number and area burnt were obtained from the Portuguese Forest Services (DGRF 2005) for the time period 1980–2005 and available at a county governmental level. Only mainland districts with complete fire statistics for their counties were used. Districts of Setúbal, Évora, and Portalegre were excluded due to gaps in fire records. For all available counties (236 in total), a set of socioeconomic and landscape variables shown in Table 1 was gathered.

Because 85–97% of fire ignitions are human caused (Moreno 1998), anthropogenic influence on fire ignition is considered. Information on human population density (persons km^{-2}) for each Portuguese county was extracted from the National Statistics Institute (INE 2001).

Table 1 Socioeconomic and landscape variables acquired/calculated for the Portuguese Districts

Socioeconomic, landscape, and climate variables used (units)	Scale	Source
Population density (persons km^{-2})	County	(INE 2001)
Road density (km of road km^{-2})	County	Derived from (IGEOE 2005)
Percentage of conifers (%)	County	(DGRF 2001)
Percentage of eucalyptus (%)	County	(DGRF 2001)
Percentage of broad leafs (%)	County	(DGRF 2001)
Phytomass (ton forest area ha^{-1})	County	(DGRF 2006)
Slope (degrees)	County	Derived from (IGEOE 1997)
Monthly temperature anomalies in the fires season (°C)	District	(Österle et al. 2003)
Monthly precipitation anomalies in the fire season (°C)	District	(Österle et al. 2003)

The influence of road network on fire ignitions in Portugal was already noted (Filipe et al. 2009). Using the line density function of ArcGis 9.2, the average road density inside the forest area was calculated for each county based on data from the Portuguese Itinerary Military Map (IGEOE 2005). Road density is assumed not to change significantly across time and therefore remains constant in the analysis. Information concerning percentage of conifers, broad-leaved species, and eucalypts (DGRF 2005) was used in the analysis in order to identify the role of vegetation type in driving fire numbers and area burnt. Values of phytomass density (DGRF 2006) (ton forest ha^{-1}) were available for each Portuguese county and are expected to help differentiate fire spread characteristics between districts with similar forest area but distinct phytomass density. Forest type and forest extent are here assumed as static as no yearly spatial record of land use change was available for the time period considered. Nevertheless, historical changes in land use namely area of agriculture converted to forest would be of great utility in assessing the role of land conversion in driving number of fires.

Fire spread rate is known to increase with increasing slope values (Santoni 1998). To test the influence of this terrain characteristic on fire spread, we used the average forest slope value of each county calculated from a digital elevation model with a spatial resolution of 250 m and vertical resolution of 1 meter (IGEOE 1997).

Due to lack of a spatially and temporally consistent network of climate stations information for the study period, climate data were acquired from the Climate Research Unit (CRU); a standard, consistent, and well-validated climate data set (New et al. 2000; Österle et al. 2003) regarding monthly temperature and precipitation (data resolution 0.5 degrees, approx. 49 km in the study area with a total of 42 cells covering Portugal). Monthly anomalies of precipitation and temperature were developed for the fire season (June, July, August and September) relative to the 1950–1980 average. Despite the coarse spatial resolution, it provided the possibility to test the influence of the climatic gradient across the mainland Portuguese districts.

Statistical analysis

Figure 1 provides an overview of the statistical analysis performed in the context of this work covering different spatial and temporal scales.

At a country level, a set of functions was fitted to the time series of numbers of fires, total area burnt, and average size of fire events. Linear, non-linear regression, and general additive models (GAM) were used to fit linear regression, sigmoid, piecewise or segmented regression functions combining several continuous linear or exponential segments with the R functions lm, nls, and gam (all statistical analysis performed using the statistical software R version 2.7.2). Akaikes information criterion (AIC) was used to select the best fitting most parsimonious model. Independent variables of population density, average slope, average phytomass density and fractions of conifers, eucalypts, and temperature anomalies were used to assess the interactions of climate and socioeconomic/landscape parameters in explaining area burnt and number of fires. The analyses were preformed with GAM with the most parsimonious models chosen on the basis of the AIC test.

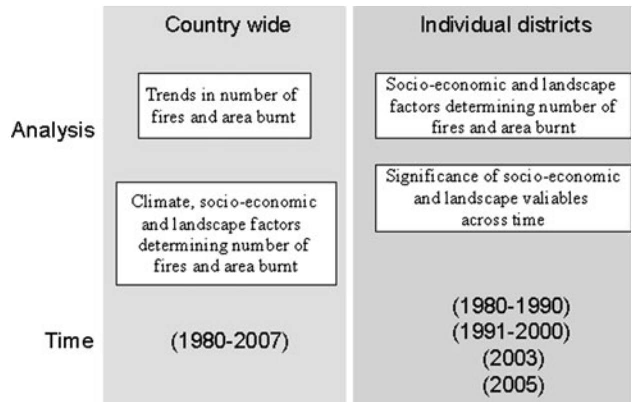

Fig. 1 Overview of statistical analysis preformed at different temporal and spatial scales

At individual district level, statistical relations between the selected variables and fires were assessed using a multiple linear regression model with stepwise backward elimination in order to find a reduced model that best explains number of fires and area burnt. The criteria for elimination consisted in removing the variables non-significantly constituting to the fit. Socioeconomic and landscape variables of all counties within a district were used as independent data and the number of ignitions or area burnt as dependent variables. Number of counties used in the stepwise backward elimination range from a maximum of 24 to a minimum of 10 for the districts of Viseu and Viana do Castelo, respectively.

In an attempt to derive the temporal dynamics of significant fire drivers in the Portuguese mainland, stepwise regression was performed for four time periods. Two decadal averages ranging from 1980–1990 and 1991–2000 and the extreme fire years of 2003 and 2005. With the separation in two decadal averages, we intend to compare the significance of fire drivers before and after the documented increase in forest fire numbers observed in the mid-1990s (Carvalho et al. 2008) and investigate the deviation of fire drivers from decadal average conditions in the severe fire years of 2003 and 2005. Three particular districts were investigated in greater detail for the role of changing socioeconomic drivers between average decadal conditions versus extreme fire years; Aveiro (high population density), Vila Real (medium population density), and Bragança (low population density).

Results

Country-wide results

Consistent with previous publications (Viegas 1998; Carvalho et al. 2008), an increasing trend in numbers of fires since 1980 up to the middle of the 1990s was noted in Portugal. The best-fitting functions (exponential increase until 1996 or two linear segments with a substantially higher slope between 1994 and 1995) both indicate an accelerated increase in the early 1990s (Fig. 2a). Later on, the time series is best described by a slight decrease in the number of fires. The most parsimonious description of the time series of area burnt is a linear increase against a very noisy background (adjusted $R^2 = 0.128$, $p = 0.035$) with a slope of $+44\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$ (Fig. 2b). The extreme fire years of 2003 and 2005 led to areas burnt clearly well above the general trend. The combined trends of number of fires and area burnt have led to a substantial decrease in the average area burnt per individual fire from approximately 20 ha in 1980 to 5 ha in the mid-1990s (Fig. 2c). Despite this apparent gain in the efficiency of fire fighting, severe fire events like the ones observed in 2003 and 2005 were not prevented, resulting in similar maximal values of average fire sizes as those observed during the 1980s and early 1990s. During the occurrence of these two fires extremes, average fire season temperature anomalies (namely from 2002 until 2005) relative to the long-term fire season average (1950–1980) were positive while precipitation values present no unusual deviation from the long-term fire season average (1950–1980).

At the inter-annual time scale, anomalies of fire season precipitation sum and area burnt were not significantly correlated (at $p < 0.05$) in any of the districts. In 13 districts, the anomalies of fire season temperatures were significantly ($p < 0.05$) correlated with area burnt. The correlation was positive for all districts, and on average, the correlation coefficient was 0.43 (min: 0.31, max: 0.58)

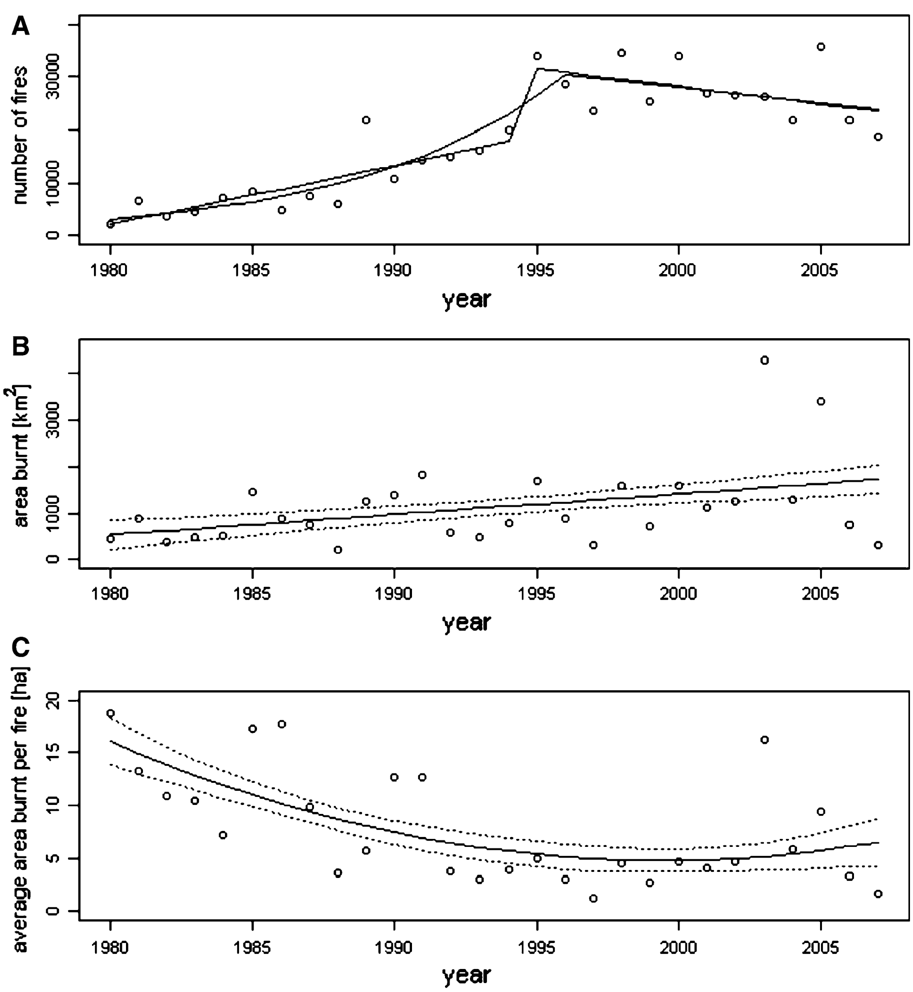

Fig. 2 Number of fires, total area burnt, and average area burnt per fire in Portugal for the period 1980–2007. For the number of fires, the two best fits are shown. For total area burnt and area burnt per fire, the best fit ± standard error of estimate is shown

indicating higher fractions of forest area burnt in warmer years. Neither temperature nor precipitation anomalies were significantly correlated with number of forest fires in any of the districts. When inter-annual variability in number of fires and area burnt is analyzed for all districts conjointly, the most parsimonious model for area burnt with fire season temperature anomalies used as explanatory variable only provides a modest (11.4%) fraction of the explained variance. On a log–log scale, average slope of forest areas explained 69.5% ($p < 0.001$) of the variance while average phytomass explained 33.9% ($p = 0.007$). The most parsimonious model for number of fires explained 41.7% of total deviance with population density as the single independent variable. This is remarkably high considering that a high fraction of variance resides in the inter-annual variation.

Individual districts results

In general, for the period 1980–1990 (Fig. 3a), higher number of fires is noted in the northern Portuguese districts than the ones located further in the south. For the second time period (1991–2000 Fig. 3b), we can observe a general increase in the number of fires across the Portuguese mainland, except for the southern districts of Setúbal, Évora, Beja, and Portalegre. In the second time period, northern regions report again the highest share of ignitions.

When within district variability was analyzed at the county level, the set of drivers obtained by stepwise backward elimination (please see colored bars indicating the significant independent variables obtained and their respective significance code) explain from 76% up to 95% of the geographical fire ignitions variability in the districts of Vila Real, Aveiro, Castelo Branco, Beja, Santarém, and Faro for the time period 1980–1990 (highlighted borders–Fig. 3a). Apart from Faro, all the above-mentioned districts present R^2 values above 75% for the period from 1991–2000. This indicates not only that the subset of variables obtained from stepwise backward elimination for these districts was able to capture much of the variability in fire numbers across time. For districts such as Coimbra, Porto, Guarda, and Viseu (highlighted borders–Fig. 3b), the performance of the chosen set of variables in explaining the number of ignitions provided a maximum of 50% of explained variability in both decadal averages.

The variables, population density and/or road network, appear as significant variables driving fire ignitions in almost all the Portuguese districts in both decadal averages (Fig. 3a, b). The influence of population density and/or road network is particularly noted in northwestern districts. In some districts, vegetation type is significant, for example, percentage of conifers and eucalypts in Castelo Branco, Leiria, and Aveiro for both decadal averages. In other districts, the type of vegetation cover seems to be

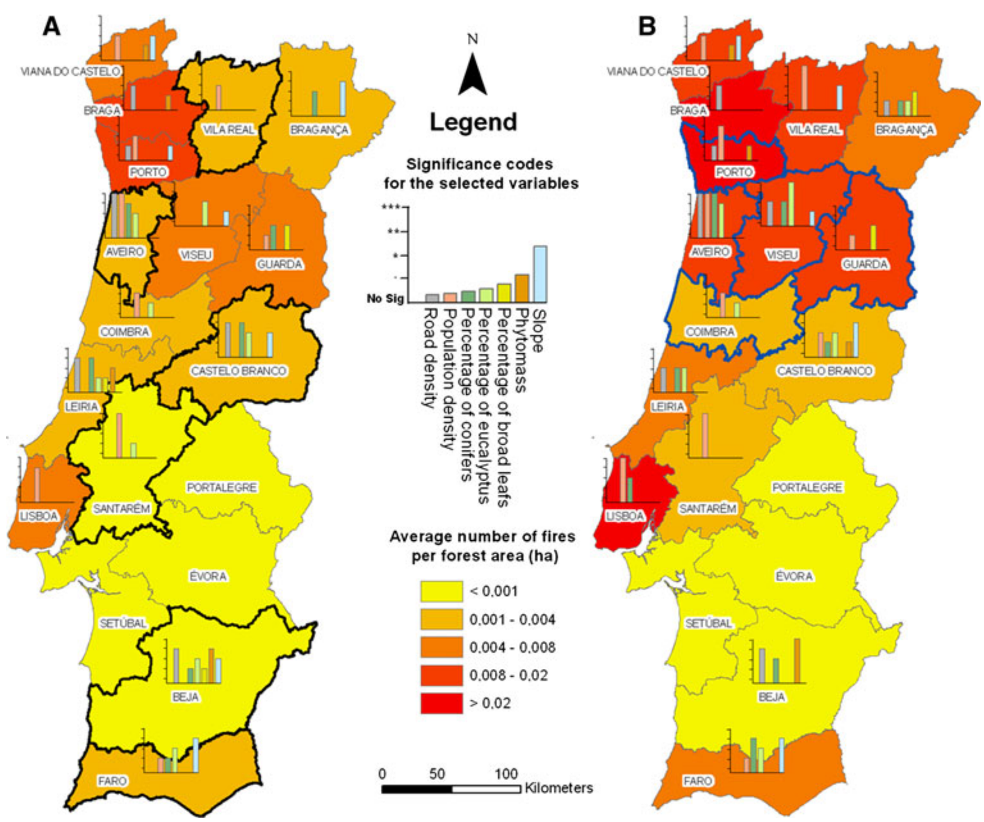

Fig. 3 Average number of fires in the Portuguese districts for the decadal periods 1980–1990 (**a**) and 1991–2000 (**b**). *Bar plots* indicate the significance levels of tested variables in explaining fire ignition variability in the Portuguese districts for the decadal averages 1980–1990 (**a**) and 1991–2000 (**b**). Borders highlighted in **a** depict districts where the significant variables explain more than 75% of number of fires in both decadal averages, except the district of Faro for the 1991–2000 period. Borders highlighted in **b** depict districts where the significant variables explained up to 50% in number of fires variability for both decadal averages

irrelevant for the number of ignitions, for example, Vila Real, Porto, and Braga for both time periods.

Significant variables for some districts (4 of 15) do not vary between the two decades. Viana do Castelo, Aveiro, Coimbra, and Faro present the same significant variables for both decadal averages, although there are some changes in the degree of significance. Minor shifts in the significant variables are noted in 6 of 15 districts. For example, in Vila Real and Lisboa, a new variable besides population density becomes significant in the second decadal average. Other minor changes can be observed in the districts of Braga and Santarém, in this case, variables related with vegetation type and phytomass density become non-significant in the second decadal average and population density is accounted as the only and highly significant variable explaining the number of fire ignitions. The remaining districts (5 of 15) present rather diverse shifts. For example, in Viseu and Bragança, road density becomes significant during the 1990s while in the 1980s, only type of forest and slope played a role in explaining the number of fires.

The number of fires per forest area had a similar distribution in both extreme years 2003 and 2005 (Fig. 4a, b, respectively). The northern districts are the ones where higher values are noted, a tendency already observed to some extent in the 1980s, and clearly since the 1990s up to 2005. Significant variables obtained for the districts of Guarda, Viana do Castelo, and Castelo Branco (3 of 15) remain constant for the two extreme years. This does not mean that the amount of explained variability in number of fires is also consistent within districts. In Castelo Branco for example, the capacity of the selected variables in explaining the number of ignitions reaches 83% in 2003 but fails to exceed 67% in 2005. For the remaining districts, results show a very heterogeneous picture on the evolution of significant variables. A closer look will be reserved to three particular districts in order to better investigate the evolution of selected variables in explaining the number of fires and area burnt over time.

For the selected districts (Fig. 5), resulting subsets of variables obtained by stepwise backward elimination provide higher values of explained variability for number of ignitions than for the fraction of area burnt.

Concerning number of fires, the selected districts maintain a fairly constant degree of explained variability (always above 50%) across different time periods. In Aveiro, significant variables and amount of explained variability remain quite constant across decadal averages. Population, road density, percentage of conifers, and eucalyptus explain up to 98% of the number of ignitions. In the extreme fire year of 2003, only population density and road density appear as significant variables and the overall R^2 drops to 86%. In 2005, percentage of conifers reappears as significant and the fit improves to similar levels like the ones observed in the decadal averages.

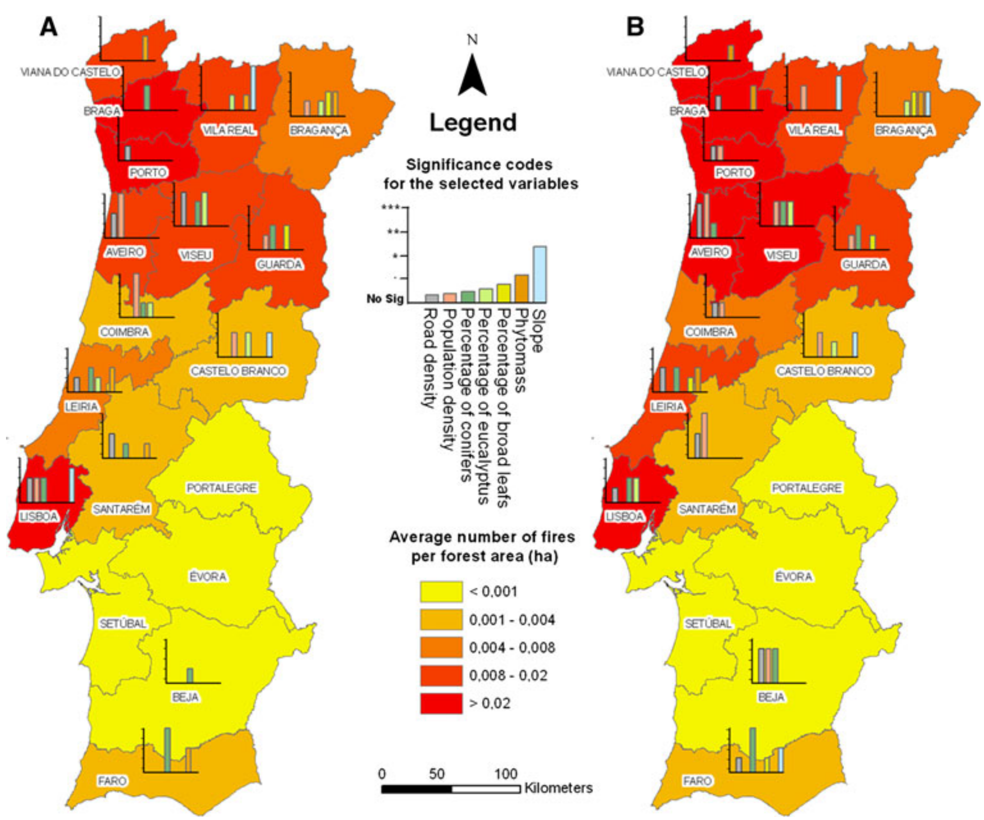

Fig. 4 Average number of fires in the Portuguese districts for the extreme fire years of 2003 (**a**) and 2005 (**b**). *Bar plots* indicate the significance levels of tested variables in explaining fire ignition variability in the Portuguese districts for the extreme fire years 2003 (**a**) and 2005 (**b**)

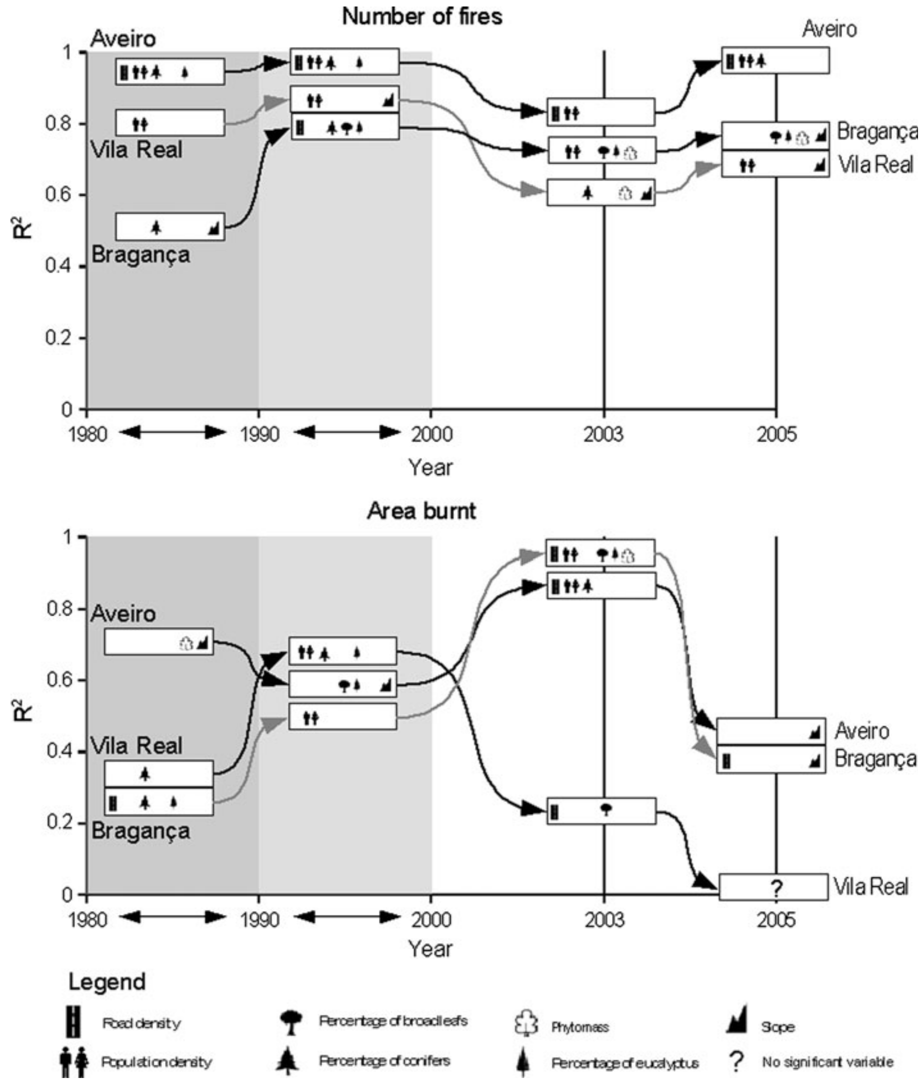

Fig. 5 R^2 and significant variables explaining number and area burnt values for selected Portuguese districts in decadal averages (1980–1990 and 1991–2000) and extreme fire years (2003 and 2005). Selected districts: Aveiro (high population density approx. 250 persons km^{-2}), Vila Real (medium population density approx. 50 persons km^{-2}), and Bragança (low population density approx. 20 persons km^{-2}) population density

Number of ignitions in Vila Real is by large extent (80 and 86%) explained by population density and population density and average slope in the first and second decadal averages, respectively. In 2003, percentage of conifers, broad leafs, and average slope are the significant variables resulting from the stepwise regression process. The amount of explained variability during this year drops considerably (61%) when compared with previous decadal averages. In 2005, population density reappears as significant and the R^2 for number of ignitions improves to 76%.

In Bragança, the first decadal average is characterized by a low R^2 value (56%) where only the variables percentage of conifers and average slope appear as significant. In the second decadal average, explained variability improves to 76% as the subset of significant variables also shifts to include road density, percentage of conifers, eucalyptus, and broad leaved species. The analysis regarding the extreme fire years produces an identical set of significant variables for 2003 and 2005. The most notable difference seems to be the shift from population density as a significant variable in 2003 to average slope in 2005. Notice that despite the shift, R^2 values remain fairly constant during the extreme years (74 and 77%).

Regarding area burnt, the R^2 values obtained are in general lower when compared with the ones observed for number of fires. This is mostly notable during the first two decadal averages and the extreme year of 2005. In fact, only in the extreme fire year of 2003, the districts of Aveiro and Bragança obtain high levels of explained variability of area burnt, 83 and 93%, respectively. This is interesting because in principle, one should expect area burnt number to be more closely related with climatic conditions (Carvalho et al. 2008, 2010), which are not included at this spatial scale of analysis. This might indicate that for particular districts, the socioeconomic and landscape factors override climatic factors both in number and extension of fires.

In the second extreme year, a smaller number of significant variables obtained by backward elimination are noted in all districts. Aveiro and Bragança only account for one and two significant variables, slope, and road density, respectively. In Vila Real, no significant variable in explaining values of area burnt was obtained via backward elimination. R^2 values drop substantially in all districts. In supplementary material, the full results for all districts and time periods can be found.

Discussion

Country-wide results show that the remarkable increase in number of fires starting in the early 1990s could not be explained by the investigated climatic factors. Monthly climatology misses meteorological variables and temporal conditions that might have been significant. In addition, the great fraction of explained variability in number of fires obtained exclusively with population density (42%) indicates that the changed fire frequency results at least in a substantial fraction from, yet unexplained, changes in human activities, land use, or flammability of biomass due to changed fuel-loads. Because original data on both number and area burnt are aggregated at county level, it remains to be explored to what extent a change in reporting practice might be a cause for the observed time-course of fire frequencies. For example, since 1990 the annual area burned is mapped based on satellite information (Carvalho et al. 2008). An increased fraction of small fires reported from the early 1990s onwards could explain the observed pattern in ignitions. This kind of reporting changes in the overall understanding of time series development remains to be explored and should be a topic of future work.

At individual district scale, a strong link between number of fires and population density and/or road density was particularly strong in the northwestern districts of Portugal, districts characterized by high and medium population densities, high number of ignitions, but, in general, relatively small area burned. This indicates that high population densities and the existence of a dense road network might lead to a quick initial fire fighting response and higher landscape fragmentation preventing the occurrence of very large fires. For some districts, the rather small amount of selected variables provides significant high fractions of explained variability for number of fires (up to 90%) both in decadal averages and in extreme years. This indicates that for particular Portuguese districts, human and landscape factors were the main drivers of forest fires across time. More interesting, however, is the dynamics of the relative importance of the selected fire drivers across time. In this respect, we found that for 10 of the 15 districts analyzed in this study, the significant variables explaining number of ignitions remain stable or suffer only minor changes in the time periods 1980–1990 and 1991–2000. In these cases, although a clear trend is hard to detect, broadly the change in significance of the variables was rather low. This means that on average, the degree of significance in the first decadal average is maintained in the second. For the 5 remaining districts, changes in both the number of significant variables and their significance were highly variable. During the extreme fire years of 2003 and 2005, considerable shifts in number and significance of fire drivers were observed across the Portuguese districts. This was verified even in districts with stable number of variables and their significance in both decadal averages.

An in-depth look at three distinct districts showed the remarkable heterogeneity of the significance of fire drivers both in time and in space even within neighboring districts. Our findings point toward a dynamic, perhaps highly nonlinear, behavior of socioeconomic and landscape fire drivers that can override the significance of climatic factors for some Mediterranean regions in extreme fire years. For some districts, R^2 values obtained concerning area burnt were lower for the investigated districts when compared with results for number of fires. In this case, the further inclusion of regional climatic parameters might help elevating the levels of explained variability.

Although climate does trigger broad favorable fire conditions across Portugal mainland, socioeconomic and landscape factors proved to determine much of the complex fire patterns at a subnational scale. We show that high fractions of regional explained variability for number of fires and area burnt can be obtained by the exclusive use of socioeconomic and landscape factors. By applying a broad range of consistent significant fire drivers explaining the occurrence and spread, we were able to observe that the significance of these drivers is remarkably variable in some Portuguese districts, both in the long term and during extreme fire years. Our findings point that forthcoming attempts on understanding and modeling future implications of climate change in Mediterranean fire regimes should include a wide range of potential socioeconomic drivers to account for shifts in significance of fire drivers over time, particularly in extreme fire years.

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