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Forest fires across Portuguese municipalities: zones of similar incidence, interactions and benchmarks

Vítor João Pereira Domingues Martinho[1]

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Abstract

Every year fires cause several problems and considerable damage to the Portuguese socioeconomic context and to forest resources and activities, despite the significant financial support, from national and European Union budgets, towards prevention. This is an annual scourge that requires multidisciplinary analysis to aid in the design of adjusted firefighting strategies. In this framework, the objective of the study presented here is to investigate if there are Portuguese regions where the incidences of fire, in terms of number of fires and burnt area, are similar, helping toward the creation of firefighting policies in cooperation with neighbouring municipalities. On the other hand, there is a need to understand the interactions of these contexts between the environment and human ecology and finally find municipalities that may be considered as a benchmark for others around them. For this, data from the Statistics Portugal (INE in Several statistics and informations, 2015. https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_base_dados), for the period 2000–2013, was used and analyzed through descriptive and cross-section techniques and data envelopment analysis (DEA) for the municipalities of Continental Portugal. For the cross-section analysis, the GeoDa (Software. GeoDa Center for Geospatial Analysis and Computation, 2015) software was used considering spatial autocorrelation methodologies and for the DEA the DEAP (DEAP V2.1—a data envelopment analysis (computer) program, 2017. http://www.uq.edu.au/economics/cepa/deap.php) program. The results show that there is spatial autocorrelation across Portuguese municipalities, in the period considered, for the variables considered, which allows for the definition of "regions of similar incidence" for which similar policies can be designed, namely those promoting cooperation among neighbouring municipalities. In turn, some municipalities may be considered as benchmarks inside zones of similar incidence.

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✉ Vítor João Pereira Domingues Martinho
vdmartinho@esav.ipv.pt

Extended author information available on the last page of the article

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1 Introduction

The amount invested and spent every year on several regions of Portugal in the prevention and fighting of wildfires is significant. This financial expenditure comes from the European Union budget, but also from national institutions and municipal budgets. There are several direct ways of prevention, as well as various indirect forms, like, among others, those related to the improvements in sustainability, environment, research, access and water points.

The different policies created for Portuguese forest management and fire prevention, namely those designed after the calamities of 2003 and 2005, were important contributions towards addressing these questions seriously and with due care and attention. The several forestry associations that exist in various Portuguese municipalities, some of which appeared as a consequence of the attention paid by the national public institutions within the sector and in the wildfires in Portugal, are interesting contributions towards sustainability in this sector. Some of these organizations of forest producers have forestry sapper teams, which are crucial for fire prevention, through the vigilance and cleaning of excess forest wood, and providing first interventions in firefighting.

The severe consequences of wildfires in Portugal, aroused interest in these issues and afforded an understanding that there are urgent new policies and that there is differing multidisciplinary research to find more strategies for this problem. In fact, every year wildfires create panic among populations, putting properties, houses, agricultural production and other material belongings in danger. Many times, it is the population and the means available for firefighting which are impotent towards dealing with the overpowering force of fires. This was demonstrative, for example, in the fires verified, in Portugal, in August of 2016 in the Madeira Archipelago and those which occurred in June (around the municipality Pedrógão Grande) and October of 2017, where inclusively people died.

The context described up until here, shows that all the contributions towards these themes are insufficient for finding new approaches in order to help the population and professionals who every day, some voluntarily, spent their time and at their expense, sometimes even paying with their own lives in very difficult situations, whilst attempting to reduce the negative impact of the wildfire phenomena.

What, indeed, is really important is to find ways to reduce the damage to populations, but also, and not least importantly, their suffering and the suffering of who for a part of the year deal with this scourge in the front-line and in administrative positions in order to maintain the structures related with these problematic operations in normal conditions.

The aim of this study is to provide an interesting contribution, among many others with alternative approaches, toward helping the diverse firefighting operators in the search for new and better adjusted policies, through the definition of "regions of similar incidence", namely by using spatial autocorrelation approaches at municipality level, and understanding the interactions of these frameworks with the environment and human ecology. To identify municipalities that can be considered as benchmarks, because their practices in firefighting, is another aim of this study, considering data envelopment analysis methodologies and the concepts of efficiency.

2 Literature survey

Anthropogenic factors are one of the leading causes of forest fires in European countries, but the associated aspects are not yet well explained (Martínez-Fernández et al. 2013). Indeed, the human factors are the principal source of forest fires in several countries, namely in Mediterranean countries, as demonstrated in studies such as Mourão and Martinho (2014) where the more populated Portuguese municipalities are those with a higher number of fires. Martínez-Fernández et al. (2013) analysed the human factors behind fires in Spain, through regression techniques, where spatial effects were also considered to capture spatial variations among Spanish municipalities. They concluded that spatial regressions as more than just an alternative to the "traditional" regressions are a complement toward investigate, namely, the non-stationary.

Other authors have considered spatial effects to research subjects related with fires and burnt areas in Europe. For example, Pons and Bas (2005) considered the spatial autocorrelation to examine the consequences of fires on natural habitats, namely in bird populations, in the Iberian Peninsula and Southern France. The consequences of the fires in the burnt areas are not always as might be expected. These studies are contributions towards understanding the patterns across the several habitats after the problems caused by fires. In a similar line, Gil-Tena et al. (2009) investigated, for Spain, changes in Mediterranean forests and the distribution of birds. The impacts of the fires on the local habitats were, also, analysed by Nowicki et al. (2015), considering the possibility of existing spatial autocorrelation, for butterfly populations in Poland, after a big fire in 2012. Still covering natural habitats, Lilleskov et al. (2004) considered these methodologies to analyse the spatial distribution of ectomycorrhizal fungi, but with data from studies for California and the Pacific Northwest. The birds, the butterflies, the fungi and other communities have their roles in the dynamics of forest ecosystems. Fire is an abiotic factor of forest disturbance and each fire is different, as well as its implications, as demonstrated, by Pausas (2006), when considering the spatial autocorrelation to perform research about the interaction between the landscape structure and the fires' characteristics. The landscape structure and its characteristics, such as the availability of biomass and fuel charge, influence the dimension of fires. These facts demand the need for observing the vegetational evolution (Alexandridis et al. 2008). In turn, the context of the fire, as well as associated conditions such as the climate (Lloret et al. 2005) and the landform (Kim and Arthur 2014), influence the capacity and the framework of regeneration for several species. The work of Kim and Arthur (2014) was carried out in eastern Kentucky, USA. Alternatively, Sousa et al. (2003) used the Moran´s I spatial autocorrelation statistical test in their study about obtaining images adjusted to the burnt area research, considering satellite imagery from Portugal, Central Africa and South America. In fact, the spatial autocorrelation methodologies have many applications across different fields.

For North America, as for the European regions, the aspects associated with spatial autocorrelation in fire analysis have, also, been considered in several studies. In this context, Wang et al. (2013) stressed the spatial effects in the assessment of Canadian fire risks, as being an interesting instrument for analysis and research. The risks of fires were, also, investigated by Crecente-Campo et al. (2009) considering the spatial effects, but for northern Spain. Developing adjusted methodologies to well determine the risks of fire and prevent its consequences and implications is fundamental in avoiding human, cultural, social, economic and environmental costs. The spatial autocorrelation instruments may give important insights into the design of appropriate techniques that with accuracy allow to conveniently assess the risk of fires across different global regions. Landis and Bailey (2005) used spatial autocorrelation techniques to reconstruct the forest organization of some centuries ago, for northern Arizona. Sometimes it is important to understand the past to better plan for the future and to avoid repeating some undesirable and negative aspects.

In other regions, such as Australia, spatial autocorrelation was, also, considered by other authors, such as Williamson et al. (2014) who analysed the influence of cattle grazing on the reduction of fire consequences, Tng et al. (2011) who investigated tropical rain forest evolution, Murphy et al. (2010) about the relationships between fire and local environments, such as vegetation, and Pearson (2002) who modelled and quantified the structure of the savanna landscapes.

A fire's behaviour, causes and implications, are a concern for many people, considering the costs associated with the consequences of the fire. In fact, fires have several interactions (direct and indirect) with the environment and human ecological contexts, namely in rural regions (which are generally less advantaged). Spatial autocorrelation techniques may be an interesting instrument in helping to understand the contexts related with fires and has been used by many authors in various perspectives and approaches, as referred to above in the literature review.

On the other hand, the consideration of data envelopment analysis and efficiency concepts in the several dimensions of forest fires seem to be interesting techniques which have not been sufficiently explored for certain regions. Gutiérrez and Lozano (2013) provide an example how the DEA can be applied in the analysis of forest fire dynamics in European Union countries, taking into account the concepts of efficiency, and how the most efficient countries may be considered as a benchmark for the less efficient regions. Efficiency is a concept that depends on several factors, but its assessment can give crucial insights for improvements in the planning and in the organization of the prevention and fighting wildfires, namely cooperating and benchmarking the most efficient regions and countries.

The relevance of this topic related with forest fires, namely in Portugal, increased significantly in the last years. In fact the consequences of the fires verified in the Madeira Archipelago (2016) and in the Portuguese Mainland (2017) put in the order of the day that there is a need to look at this problematic situation with attention and create conditions to prevent these events from reoccurring. The main causes of extreme forest fires in Portugal are related to desertification of the interior, abandonment of land and agriculture and the consequent increase of the tinder/fuel mass (Nunes and

Lourenço 2017). Of course, global warming and climatic conditions contribute to the dimension of the consequences (Ruffault et al. 2018), as verified, for example, in the Madeira Archipelago in 2012 (Liberato et al. 2017). Considering a report from the Institute for Conservation of Nature and Forestry, for the period 01 January-16 October of 2017, in 2017, comparatively with the last 10 years, there were 1% less fires and 407% more burnt area. On the other hand, the districts more affected, in terms of burnt area, were Coimbra (around 25% of the total until 16 October), Castelo Branco (13%) and Viseu around 12% (ICNF 2017). Another important aspect about the sources of extreme forest fires, is, sometimes, the lack of adjusted resources to deal with unusual occurrences such as those verified in June of 2017 in Pedrógão Grande (Viegas et al. 2017). Finally, the forest fire policies seem to be more reactive than proactive, in Portugal, namely after extreme fires and this may not be the best way to effectively curb the extreme consequences of these phenomena (Mourão and Martinho 2016).

3 Materials and methods

Considering the objectives for this study data from the INE (2015) was used for the following variables: forest fires (number), burnt area (ha), average burnt area (ha) and the percentage of burnt forest area. These variables were considered disaggregated for the municipalities of Continental Portugal and for the period 2000–2013 (except for the last variable, where the series begin in 2007).

These data will be first analysed in a more descriptive perspective and later worked through spatial autocorrelation methodologies and using the GeoDa (2015) approaches with the objective of finding Portuguese regions (municipalities) with similar wildfire incidence. The spatial autocorrelation analyses the possibility of the values of a determinate variable, in a spatial unity, to be correlated with the values of the same variable in the neighbouring spatial unities (in this case municipalities). In general, literature refers to the possibility of the existence of global and of local spatial autocorrelation, analysed through Moran´s I statistics (GeoDa 2015; Martinho 2015a, b).

The global spatial autocorrelation considers the possibilities of interactions for all the spatial municipalities considered. The positive values of the Moran´s I signifies positive global spatial autocorrelation (the values of a variable are positively auto correlated in the several spatial unities) and where negative values imply the inverse. The local spatial autocorrelation analyses the possibility of interactions with its neighbours for each individual municipality, identifying or negating clusters of municipalities. For the local spatial autocorrelation, the GeoDa (2015) considers the possibility of positive spatial autocorrelation for high–high and low–low values and of negative spatial autocorrelation high–low and low–high values among the several neighbouring municipalities. When dealing with spatial issues, the questions related with the distances or contiguity among the spatial unities considered are crucial. Therefore, in this study a queen matrix of contiguity was utilized which considers in all directions the first neighbours (matrix of contiguity with one neighbour), the second (matrix of contiguity with two neighbours) and so on.

After this, the identification of Portuguese regions with similar wildfire incidence, in these municipalities, and the data description will analyse the interrelationships between forest fires with the environment and human ecology, through the analysis of data obtained from INE (2015) relative to the evolution of socioeconomic contexts and the environment.

4 Data analysis about wildfires

Before beginning deeper analysis, it is important to make an overview of the evolution of the values of the variables considered (Table 1 and Fig. 1). Table 1 reveals that, on average across the Portuguese municipalities, the years of 2000, 2005, was where there were more forest fires (123 and 129, respectively), however it was the years of 2003 and 2005 where there was more burnt area (respectively, 1577 and 1233 ha). The average burnt area (area burnt/number of forest fires), over the municipalities of Continental Portugal, was higher in 2003 (72 ha/forest fire). Finally the forest fires consumed about 3%, in 2010, and 4%, in 2013, of the forest area. In fact, Portugal is among the European Union countries that has been punished the most by forest fires over the last decades, which makes all the technical and scientific contributions in these fields for the Portuguese context crucial insights into finding more adjusted approaches towards the prevention and combat against this phenomena that each year brings serious consequences to the landscape characteristics and dynamics. It is important to consider the social, cultural, economic and environmental Portuguese characteristics to better and more efficiently avoid the worrying implications of forest fires.

Figure 1 shows that the greater incidence of forest fires (FIREN) was in the municipalities of Paredes, Santa Maria da Feira, Penafiel and other neighbouring municipalities in the littoral North of Portugal, as well as around Lisbon. On the other hand, the higher incidence in terms of burnt area (AREAB) was in Guarda, Sabugal and Seia and other municipalities located, namely, in the interior Center of Portugal. The average burnt area (AREABA) shows greater values in Nisa, Gavião and Crato and other municipalities of the interior and south of Portuguese regions. This shows that here is where the fires had more significant dimensions in the period considered (2000–2013). Finally, the percentage of burnt forest area (AREABP) was more relevant in Peso da Régua, Tondela and Fafe, and the neighbouring municipalities in the Northern and Central Portuguese regions.

In fact, Fig. 1 reveals that in the Portuguese Mainland territory it is possible to find Portuguese zones with similar incidence of different phenomena related with forest fires as are those associated with the number of forest fires, burnt area and average burnt area. This could be considered to concentrate efforts by different municipalities to prevent and combat wildfires. Financial restrictions bring about serious difficulties for Portuguese municipalities to manage their budgets, where the context of the municipalities is not sufficiently diverse. In this framework, the municipalities that already cooperate in the design of some strategies, in the intermunicipal communities for example, could bring about questions related with forest fires which are more suitable for the order of the day and reinforce common efforts. This could be a strategy towards increasing resources for forest fire prevention and combat, that seems to be much needed, considering the recent incidences and severity of the forest fires across several regions of Portugal.

Table 1 Data in average, among the Continental Portuguese municipalities, for some variables related with forest fires and burnt area

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Forest fires (number)	123	97	96	94	80	129	74	73	54	94	79	91	76	69
Burnt area (ha)	587	414	458	1577	480	1233	279	123	67	334	508	273	411	585
Average burnt area (ha)	8	9	10	72	21	15	8	4	1	3	7	4	8	12
Percentage of burnt forest area (%)								1	0	2	3	2	2	4

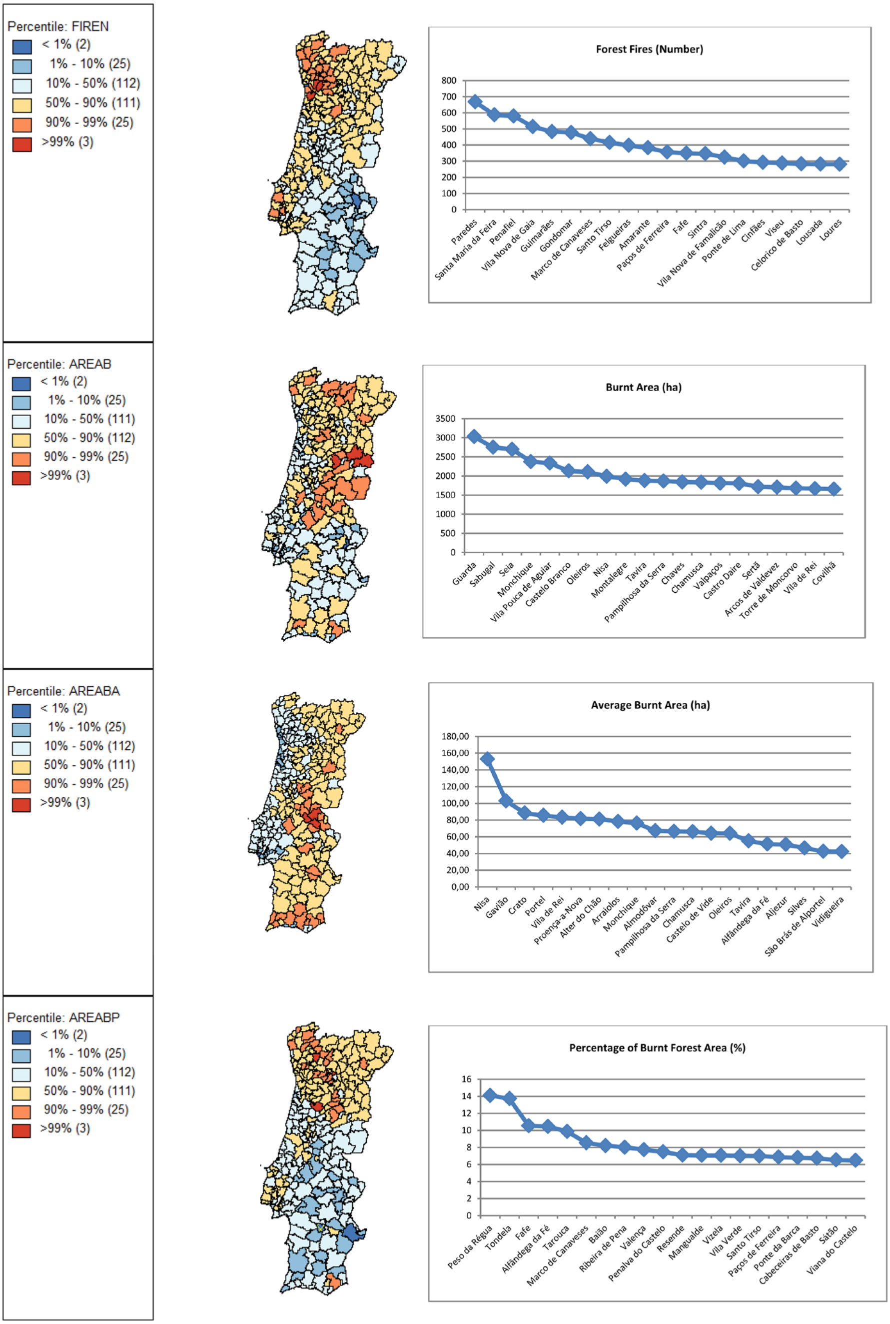

Fig. 1 Distribution of the values, on average for the period 2000–2013, associated with some variables related with forest fires and burnt area

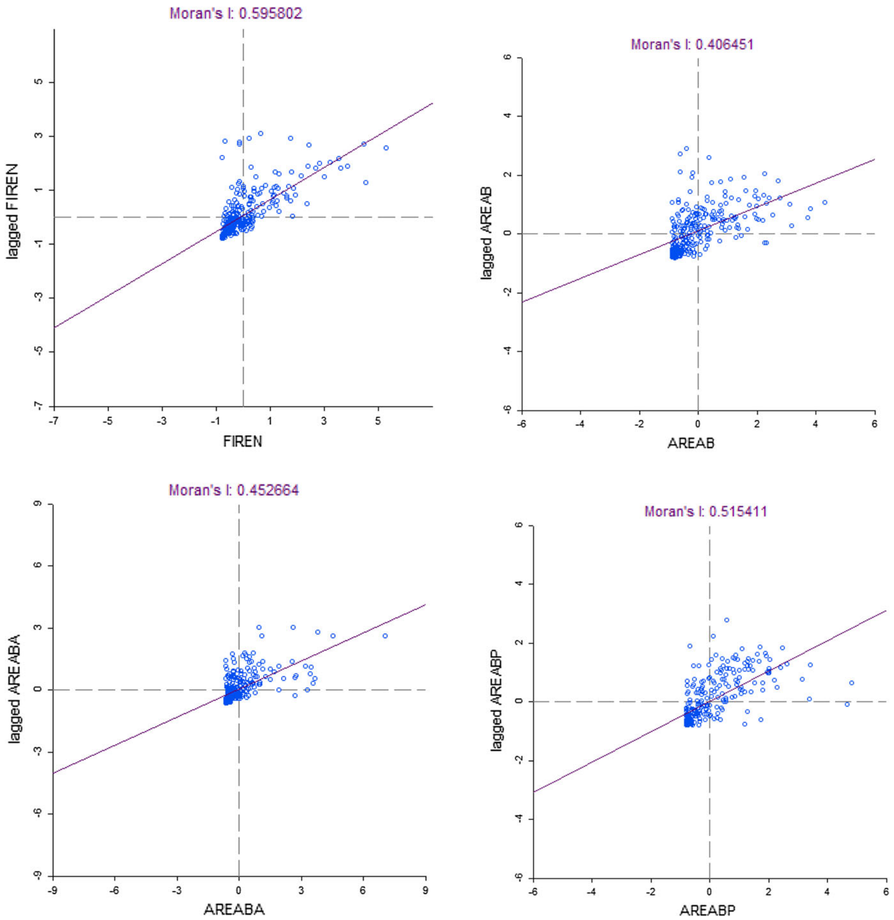

Fig. 2 Global spatial autocorrelation for some variables related with forest fires and burnt area, on average for the period 2000–2013, considering a queen matrix of contiguity with one neighbour

5 Global and local spatial autocorrelation

Figures 2, 3, 4, 5, 6, 7 present the values for the Moran´s I statistical test for the global spatial autocorrelation. In Fig. 2 (for one neighbour) it is possible to observe strong and positive global spatial autocorrelation for the four variables considered, namely for the number of forest fires and the percentage of burnt forest area, with Moran´s I of 0.596 and 0.515. The lower Moran´s I is observed for the burnt area (0.406). This reveals that the spatial autocorrelation is higher in the number of forest fires than in the burnt area.

Figure 3, with two neighbours, shows a tendency similar to that described for Fig. 2, but the reductions in the Moran´s I were less relevant in the percentage of burnt forest area, which maintains a value for this statistical test of 0.501, in comparison with the

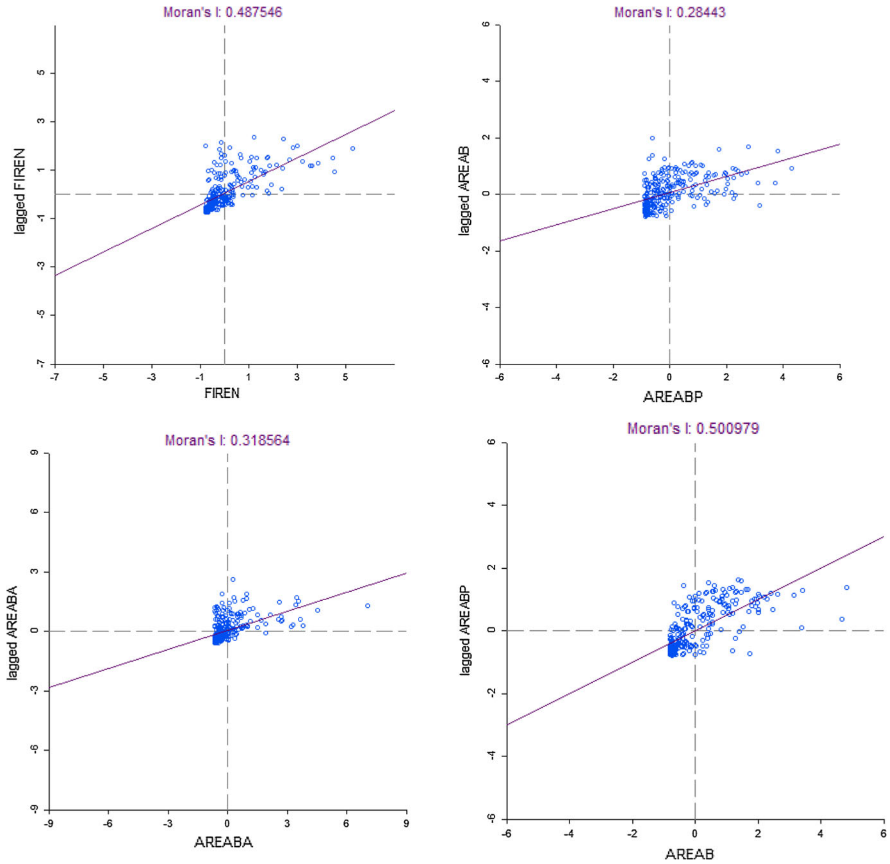

Fig. 3 Global spatial autocorrelation for some variables related with forest fires and burnt area, on average for the period 2000–2013, considering a queen matrix of contiguity with two neighbours

values for the other variables that are as follows: 0.488 for the number of forest fires; 0.284 for the burnt area; and 0.319 for the average burnt area.

The values of the Moran´s I shown in Fig. 4 (for three neighbours), show significant reductions, namely, for the burnt area (0.180) and for the average burnt area (0.158). The other variables maintain relatively high values for the Moran´s I.

The tendency in Figs. 5 and 6 is more or less similar to that referred to before for Figs. 2, 3 and 4. Figure 7, for six neighbours in the queen matrix of contiguity, reveals for the first time a negative value for the Moran´s I and this result appeared for the average burnt area (−0.042). The other variables have remained with the following results for this statistical test: 0.106 for the number of forest fires; 0.028 for the burnt area; and 0.282 for the percentage of burnt forest area.

These contexts previously described clearly illustrate that the burnt area and the average burnt area are the variables where the spatial autocorrelation is weaker for one neighbour and where the values decrease more when the number of neighbours is increased. These results confirm that the spatial autocorrelation is greater in the number

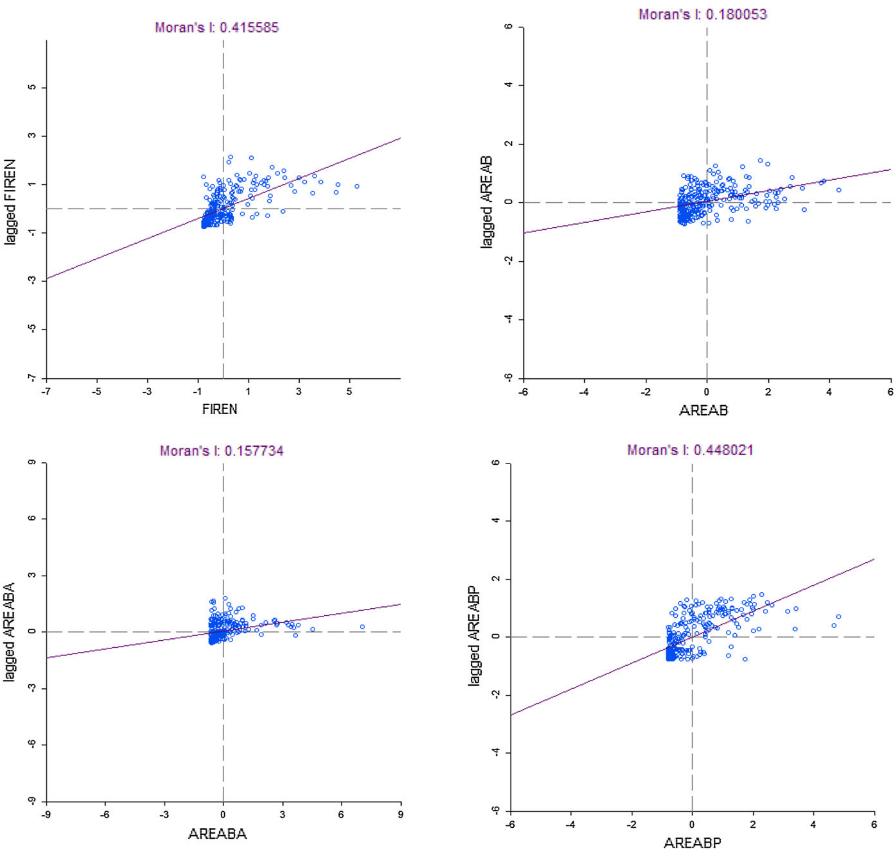

Fig. 4 Global spatial autocorrelation for some variables related with forest fires and burnt area, on average for the period 2000–2013, considering a queen matrix of contiguity with three neighbours

of forest fires than in the burnt area, which is an important insight, namely in terms of strategic planning and design. This means that it will be easier to design policies to prevent the number of wildfires, for example, in one municipality with positive impacts of prevention on the neighbouring municipalities than in the prevention of the consequences of the fires (burnt area and average burnt area, for example).

In fact, the existence of spatial autocorrelation is an interesting opportunity to design policies to be implemented in some municipalities in order to be spread out to its neighbours, allowing for reduction in costs, and for municipalities with similar characteristics to join forces.

Figures 8 and 9 present the values for local spatial autocorrelation, for each individual municipality. For the local spatial autocorrelation the GeoDa (2015) also considers the statistical test Moran´s I, as referred to before.

In these two figures the dark red represents positive local spatial autocorrelation for high values of the correspondent variable (the designated local spatial autocorrelation high–high), the dark blue indicates positive local autocorrelation for low values (the

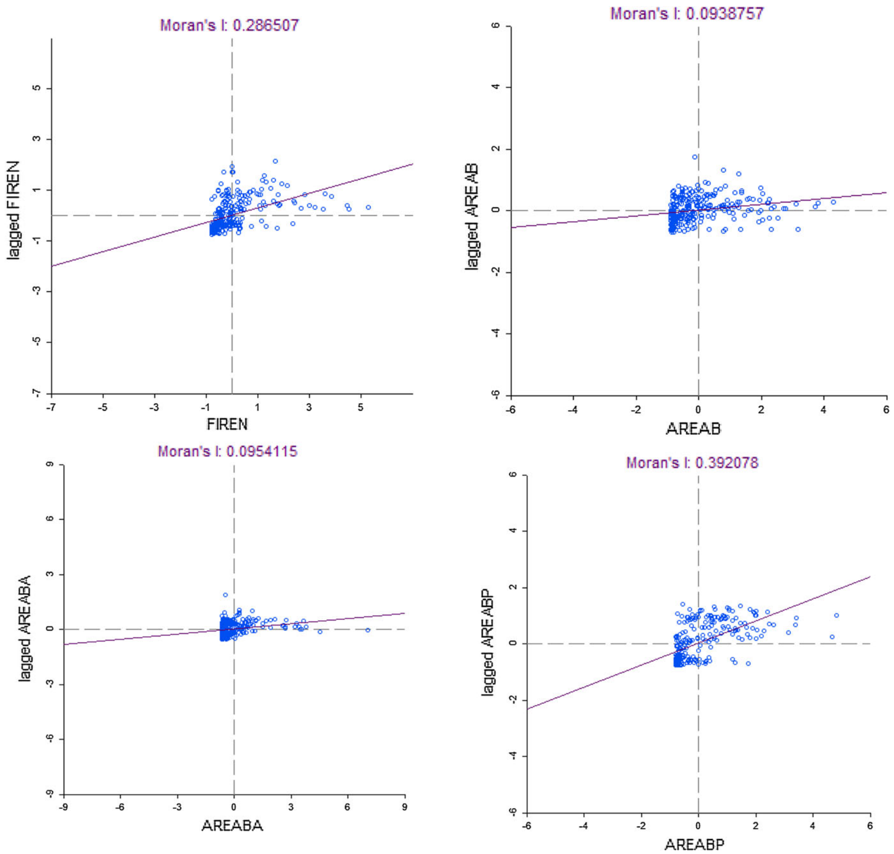

Fig. 5 Global spatial autocorrelation for some variables related with forest fires and burnt area, on average for the period 2000–2013, considering a queen matrix of contiguity with four neighbours

known local spatial autocorrelation low–low). The light blue and red are results for negative local spatial autocorrelation and the white represents no local autocorrelation.

Figure 8 (queen matrix of contiguity for one neighbour) reveals for the number of fires a positive local spatial autocorrelation, for high values, namely around the perimeter of the municipalities of Ponte Lima, Boticas, Ovar and Arouca. The burnt area has high positive local spatial autocorrelation around Montalegre, Vinhais and Vila Flor, as well as in the perimeter around Pinhel, Arganil, Abrantes and Castelo Branco. The average burnt area presents high–high local spatial autocorrelation in Central and Southern Portugal and the percentage of burnt forest area in the Northern region, namely the littoral North.

Figure 9, with a queen matrix contiguity for six neighbours, presents a similar tendency of that presented for Fig. 8, with one neighbour for the local spatial autocorrelation, but as expected having a different pattern.

The analysis performed in the previous sections shows that it is possible to identify, regions of greater incidence in Portugal, namely in terms of forest fire numbers and

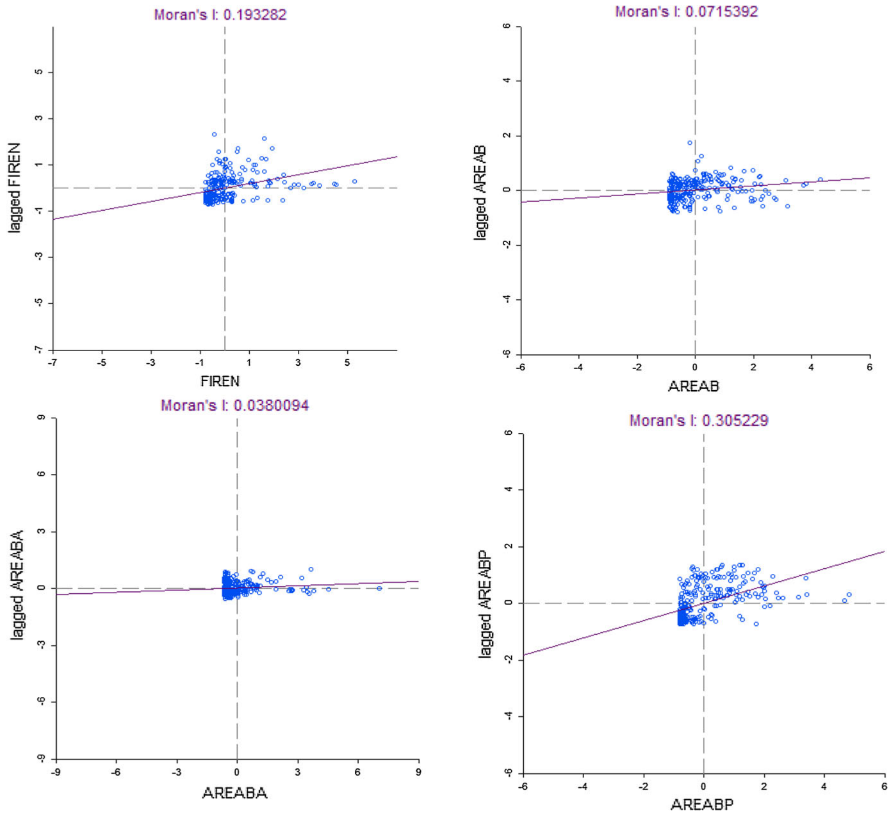

Fig. 6 Global spatial autocorrelation for some variables related with forest fires and burnt area, on average for the period 2000–2013, considering a queen matrix of contiguity with five neighbours

burnt areas, with interesting possibilities for cooperation among neighbouring municipalities, because they are spatially auto correlated in the referred to variables, meaning that some actions in one municipality may have effects upon its neighbours.

6 Interactions of wildfires with the environment and human ecology

To better understand the interrelationships between wildfire incidences and their severity in Portuguese municipalities, in Tables 2 and 3 (for the forest fires and burnt area, respectively) some variables are shown which aim to capture the dynamics, at this spatial level, related with the environment and human ecology (transdisciplinary subject related with several human dimensions, from natural to social). For this and considering the availability of data for Portuguese municipalities, (following, for example, studies such as Mourão and Martinho 2014 and Martinho 2016) the aging index (number), investments in protection of biodiversity and landscape (euros), investments in prevention and fighting forest fires (euros) and effective growth rate of the population (%), were all considered. Noting that the investments in prevention of and fighting the forest fires is a part of the investment in the protection of biodiversity and landscape.

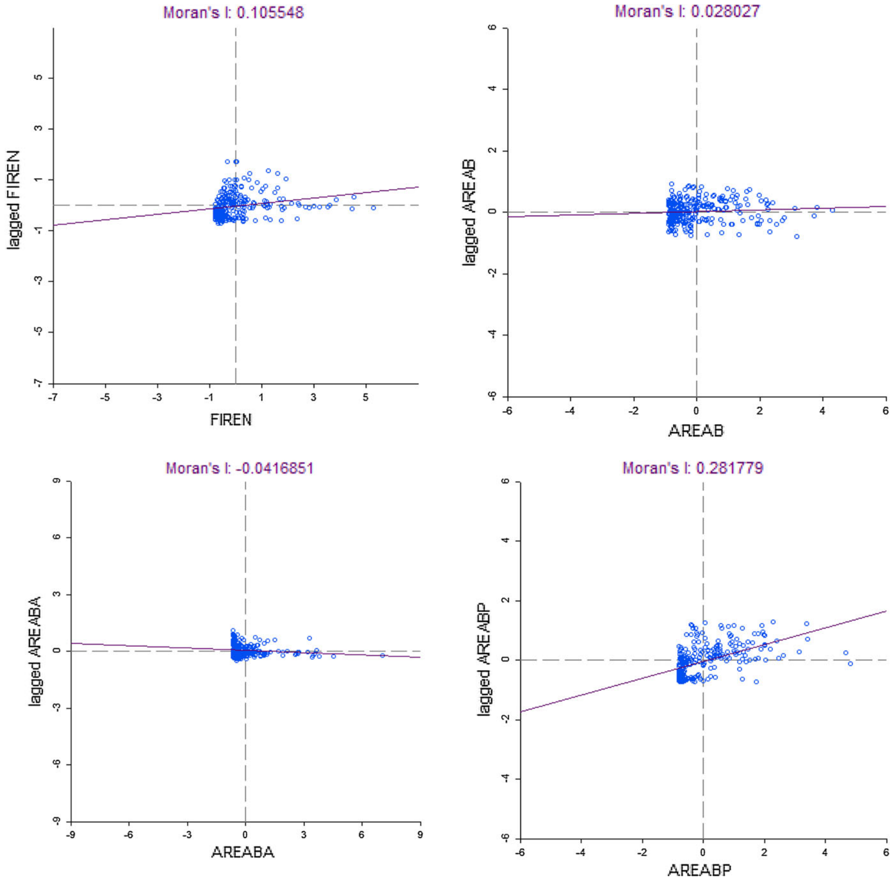

Fig. 7 Global spatial autocorrelation for some variables related with forest fires and burnt area, on average for the period 2000–2013, considering a queen matrix of contiguity with six neighbours

With the aging index and the effective growth rate of the population the aim is to capture dynamics related with social and economic human dimensions in the municipalities. In fact, the cities and towns with greater economic performance and employment attract more people. The investments in protection of biodiversity and landscape, investments in the prevention of and fighting forest fires allow us to understand the concerns of each municipality for the environment and forest fire prevention.

These variables related with the environment and human ecology will give interesting tips/hints about the interrelation between dimensions with forest fires and the burnt area and about the current and future strategies and realities of each municipality in these fields.

The municipalities presented in Tables 2 and 3 are selected considering the data analysis performed earlier (municipalities with more forest fires and burnt area, respectively) and the spatial autocorrelation overview (municipalities with local spatial autocorrelation and inside a cluster zone with higher values for the referred variables,

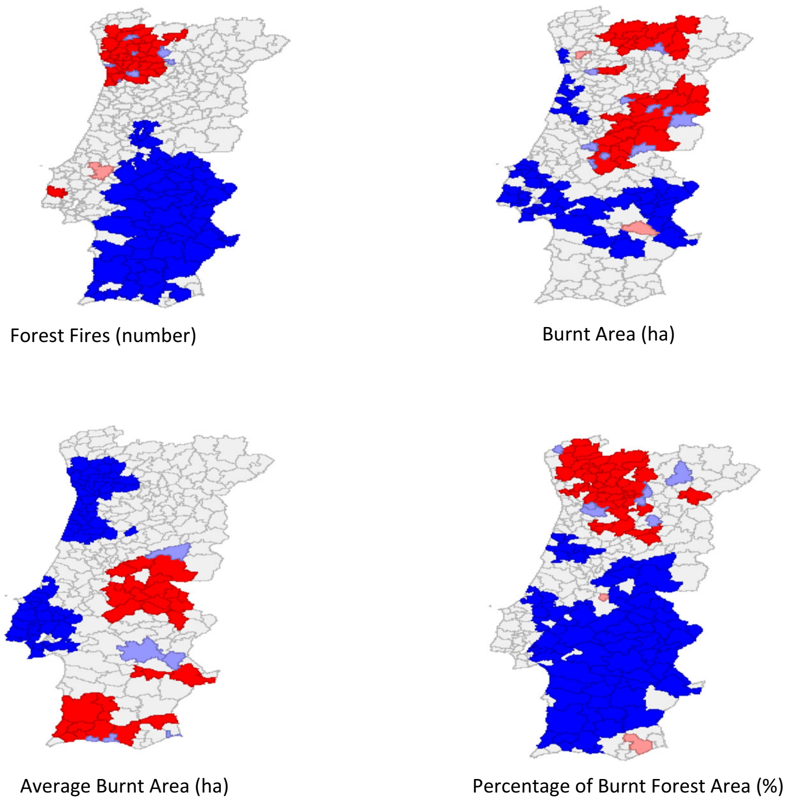

Fig. 8 Local spatial autocorrelation for some variables related with forest fires and burnt area, on average for the period 2000–2013, considering a queen matrix of contiguity with one neighbour

fires and burnt area). These municipalities show two of the more important clusters for forest fires and the burnt area, but as the data analysis and the spatial autocorrelation show, others can be found.

In Table 2, the values for the municipalities with a higher number of forest fires are shown. In this table, forest fires are the only variable in an average number (over the period considered) since the others are calculated from the ratios among the average over the period 2000–2013 for each municipality and the national average presented at the bottom of the table in bold. Ratios higher than 1 are relative to municipalities with values above the national average and vice-versa. In Table 3 the idea is the same, but now for the burnt area in ha. In these tables the five municipalities with a higher value for the number of forest fires, burnt area, investments in protection of biodiversity and landscape and investments in prevention and fighting forest fires are italicized. For the aging index and effective growth rate of the population, the lower values were stressed.

Considering the description previously made, in Table 2 the municipalities considered with a more average number of forest fires and inside the spatial cluster were around the municipality of Paredes, Santa Maria da Feira and Penafiel. In general, the literature shows that the regions of a higher and younger population have higher

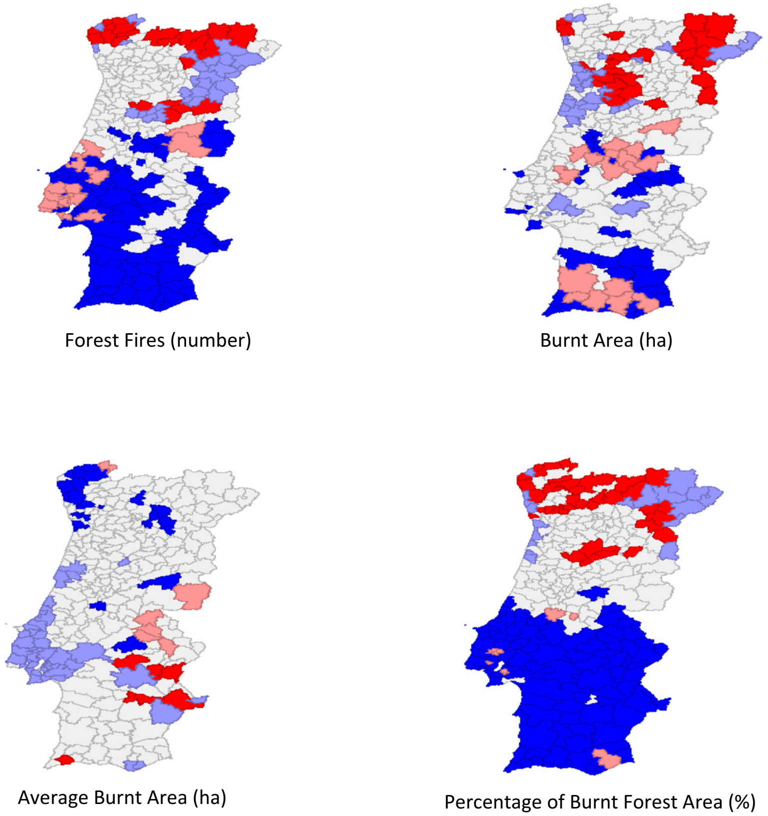

Fig. 9 Local spatial autocorrelation for some variables related with forest fires and burnt area, on average for the period 2000–2013, considering a queen matrix of contiguity with two neighbours

numbers of forest fires and this is confirmed in Table 2 by the ratios of the aging index (all below 1, so inferior to the national average) with the lower values in Lousada, Paços de Ferreira and Paredes and by the ratios of the effective population growth rate (with a relevant number of municipalities with a negative value for this variable a sign that the growth rate was positive and became negative when divided by the national average that is negative). The positive ratios for the population variation are relative to a negative growth rate. The municipalities that gained population above the national average were Lousada, Paços de Ferreira, Paredes, Vila Nova de Famalicão and Vila Nova de Gaia. In any case, there are some differences in terms of human ecology among these municipalities. In terms of environment, the disparities among the values of the ratios related with investments in protection of biodiversity and landscape and in prevention and fighting forest fires are, also, relevant. There are municipalities with 0 euros (INE 2015) applied in investments related with the protection of biodiversity and landscape and with prevention and fighting forest fires, such as Celorico de Bastos, Cinfães, Penafiel (one of the municipalities with a greater average of forest fires) and

Table 2 Ratios among the average over the period considered (2000–2013), for each municipality, and the national average (presented at the end of the table) for the several variables related with forest fires (exception for forest fires that are in an average number)

Portuguese municipalities	Forest Fires (N°)	Aging index	Investments in protection of biodiversity and landscape	Investments in preventing and fighting forest fires	Effective growth rate of the population
Amarante	383.14	0.48	*0.77*	*1.66*	1.39
Celorico de Basto	283.00	0.64	0.00	0.00	0.65
Cinfães	293.14	0.70	0.00	0.00	2.75
Fafe	349.71	0.51	0.57	*1.24*	0.89
Felgueiras	398.00	*0.33*	0.44	*0.76*	– 0.33
Gondomar	477.71	0.47	0.04	0.00	– 0.71
Guimarães	*483.29*	0.41	*0.65*	0.46	0.18
Lousada	281.57	*0.28*	0.32	0.69	*– 1.52*
Marco de Canaveses	439.43	0.36	0.40	0.71	– 0.45
Paços de Ferreira	356.64	*0.29*	0.41	*0.90*	*– 1.86*
Paredes	*668.00*	*0.30*	0.04	0.09	*– 1.11*
Penafiel	*580.57*	*0.35*	0.00	0.00	– 0.01
Ponte de Lima	301.14	0.64	*12.90*	*1.26*	0.46
Santa Maria da Feira	*587.43*	0.45	*1.49*	0.06	– 0.96
Santo Tirso	416.43	0.59	0.14	0.31	0.43
Vila Nova de Famalicão	325.36	0.41	0.00	0.00	*– 1.25*
Vila Nova de Gaia	*513.64*	0.49	*0.95*	0.31	*– 1.31*
National averages considered for these calculations		**174.95 (number)**	**42.37 (Thousand euros)**	**19.53 (Thousand euros)**	**– 0.35 (%)**

Vila Nova de Famalicão. On the other hand, many of these municipalities have ratios for these environmental investments below 1 (below the national average).

This analysis reveals that, in fact, there are visible differences among these spatial unities and that more cooperation will be required between these municipalities to jointly define policies for environmental preservation, forest fire prevention and tackling forest fires.

Table 3 confirms that Guarda, Sabugal and Seia are the municipalities with a greater average ha of burnt area. The less populated regions, in general, are more plausible candidates for burnt forest area and this is shown by the ratio of the aging index (above 1 for the great part of municipalities) and the ratio associated with the effective growth

Table 3 Ratios among the average over the period considered (2000–2013), for each municipality, and the national average (presented at the end/bottom of the table) for the several variables related with burnt area (exception for the burnt areas that are in average ha)

Portuguese municipalities	Burnt area (ha)	Aging index	Investments in protection of biodiversity and landscape	Investments in preventing and fighting forest fires	Effective growth rate of the population
Castelo Branco	*2131.07*	*0.99*	0.05	0.11	*0.39*
Chamusca	1833.92	1.27	*5.33*	0.25	3.16
Covilhã	1656.93	*0.96*	0.11	0.14	*1.77*
Guarda	*3028.43*	*0.78*	0.46	*0.68*	*1.11*
Nisa	1990.08	2.10	*1.07*	0.04	4.31
Oleiros	*2106.07*	2.59	0.51	*1.11*	4.46
Pampilhosa da Serra	1866.21	2.67	*1.45*	0.30	4.36
Sabugal	*2751.50*	2.54	0.44	0.39	4.67
Seia	*2696.21*	*1.11*	*2.33*	*4.08*	3.52
Sertã	1717.86	*1.16*	*4.74*	*0.98*	*1.75*
Vila de Rei	1669.22	1.92	0.53	*0.43*	*− 0.53*
National average considered for these calculations		**174.95 (Number)**	**42.37 (Thousand euros)**	**19.53 (Thousand euros)**	**− 0.35 (%)**

Table 4 Summary statistics for the average values over the period 2000–2013 for the variables average burnt area, number of firefighting teams and number of firefighters

Variable	Obs.	Mean	Std. Dev.	Min	Max
Average burnt area (average ha/number of forest fires)	19	73.30	25.61	39.38	152.91
Number of firefighters team (average)	19	1.05	0.21	0.93	1.93
Number of firefighters (average)	19	78.21	35.13	41.00	168.86

rate of population (positive and above 1). In any case, there are also some differences between these spatial unities. On the other hand, the investments in environmental protection and in forest protection need a common and unified strategy.

7 Identifying municipalities as benchmarks

Combining the number of forest fires and the burnt area analysed in the previous section, in this section the average burnt area (hectares of burnt area by the number of forest fires) is considered, as a basis for the explained variable, for data envelopment analysis. The variable average burnt area is available in the Statistics for Portugal (INE 2015), and the methodology considered for its obtainment presented on the following page of Statistics Portugal: https://www.ine.pt/bddXplorer/htdocs/minfo.jsp?var_cd=0001147&lingua=PT (INE 2015).

For the DEA the procedures proposed by DEAP (2017) and Coelli (1996) were considered for an input-oriented model, allowing for variable returns to scale. This was done using the inverse of the average burnt area as output and the number of firefighters and the number of firefighter's teams as inputs (the data for these variables as inputs were obtained from INE 2017), for the municipalities with higher values for the average burnt area, taking into account the spatial autocorrelation and the data analysis carried out earlier. The choice of the referred variables as inputs is mainly governed by the availability of statistical information for the Portuguese municipalities and the inverse of the average burnt area as output following studies such as those by Özden (2016). The DEA methodologies consider the concept of an efficiency frontier, where the most efficient municipalities (in this case) are considered and are used as benchmarks for the other less efficient municipalities. In the data envelopment analysis the inefficiencies are measured through the radial and slack movements, and the optimal dimension of the unities analysed is quantified by the scale efficiency (ratio among the technical efficiency from the constant returns to scale and the technical efficiency from the variable returns to scale). Considering the analysis performed in the previous sections the nineteen municipalities with a higher average burnt area (Table 4) were considered and almost all of these municipalities have only 1 firefighting team and a number of firefighters ranging from between 41 (Portel) and around 169 (Silves).

Table 5 Summary statistics for the scale efficiency obtained through DEA (multi-stage)

Variable	Obs.	Mean	Std. Dev.	Min	Max
Technical efficiency from constant return to scale	19	0.26	0.24	0.06	1.00
Technical efficiency from variable return to scale	19	0.38	0.26	0.11	1.00
Scale efficiency	19	0.63	0.19	0.26	1.00

Taking into account that the firefighters do not combat only forest fires, they have other functions such as the combat of other fires and health care, in the DEA the number of firefighting teams and the number of firefighters in each municipality were adjusted by the percentage of the number of services developed in the combat of forest fires in the total of the services provided within the respective region. This data for the services provided by the firefighters is available in the INE (2017) for the Portuguese NUTs III and are assumed values from 0.21% in NUTs III Baixo Alentejo to 2.00% in the NUTs III Região de Coimbra.

While there were forest fires, the number of firefighters was not sufficient, however the available teams could be better managed in a framework of better efficiency for the several functions developed. For the concrete case of the municipalities analysed in this section, the results from the data envelopment analysis shows that there are differences between the Portuguese Mainland municipalities (Table 5), in terms of efficiency in firefighting (in fact the scale efficiency has a mean of 0.63 and changed between 0.26 and 1), but the municipalities of Almodôvar and Vidigueira are the more efficient in the management of firefighters available in order to reduce the average burnt area. Almodôvar was considered 17 times as a benchmark and Vidigueira 8 times. This proves that the Portuguese municipalities may cooperate to reduce the incidence and severity of forest fires and can do benchmarking between each other in an endeavour to improve the efficiency in firefighting.

8 Discussion

The data analysis for the period 2000–2013, on average across the Mainland Portuguese municipalities, shows that the years of 2000 and 2005, were those where more forest fires occurred and the years of 2003 and 2005 where there was more burnt area. On the other hand, the average burnt area was greater in 2003 and the percentage of burnt forest area consumed was about 4%, in 2013.

At a spatial level, the municipalities of Paredes, Santa Maria da Feira and Penafiel were the municipalities with a greater number of forest fires, in average over the period considered (2000–2013), 668, 587 and 581, respectively. Sousel, Monforte and Porto, registered, on average over this period, 1, 1 and 0 forest fires. Guarda, Sabugal and Seia presented the greatest burnt area, on average from 2000 to 2003, respectively

3028, 2752 and 2696 hectares. The Portuguese municipalities with the least areas burnt were Entrocamento, Borba and Porto. The average burnt area with higher values in Nisa, Gavião and Crato (152.91; 102.94; and 88.29 hectares). The municipalities with lower values for this variable were Murtosa, Almada and Ílhavo (0.10; 0.10; and 0.09 hectares). On the other hand, the percentage of burnt forest area, on average over the period 2007–2013, was higher in Peso da Régua, Tondela and Fafe, 14, 14 and 11%, respectively, in contrast with the municipalities of Vila de Rei, Moura and Alvito, which were those with a lesser percentage of areas burnt.

These values reveal, in the period considered, a tendency of incidence of the number of forest fires in the littoral, namely the North of Portugal, and more burnt area in the interior, namely the Center. In contrast, there is more average burnt area (burnt area/number of forest fires) in the interior, namely the South, and a greater percentage of burnt forest area in the North. This is in line with authors such as, for example, Martínez-Fernández et al. (2013) and Mourão and Martinho (2014) who demonstrated the influence of the population density and the economic dynamics upon the incidence and severity of forest fires.

The results for the Moran´s I statistical test, for spatial interdependence, presented positive and strong global spatial autocorrelation for the variables considered, until the sixth neighbour in a queen matrix of contiguity, confirmed by the values for the local spatial autocorrelation. The results for the spatial autocorrelation confirm the data analysis that there are clusters (sets of municipalities) with more/less wildfires or burnt area. From a technical and conceptual perspective, this means that when a fire occurred in a Portuguese municipality inside a cluster with higher incidence and severity, the probability of occurrence and spread to the neighbours' municipalities is high. This suggests that the Portuguese municipalities inside the clusters with higher probabilities of risk and damage should cooperate with each other to effectively prevent and combat the wildfires, optimizing resources and reducing the consequences.

Based on these findings the interrelationships between the forest fires/burnt area, the environment and human ecology variables (for the clusters of municipalities with a higher average number of forest fires and with a greater average burnt area) reveals that, for example, the investment in environmental protection, forest fire prevention and fighting forest fires is very low in some municipalities inside each cluster. This could be mitigated with more cooperation between the neighbouring municipalities.

On the other hand, the data envelopment analysis demonstrates that the efficiency of the municipalities in reducing the average burnt area is significantly different, but the municipalities of Almodôvar and Vidigueira may be considered as a benchmark for the other, less efficient municipalities, in improving their firefighting tactics. This is in line with the findings of Viegas et al. (2017), showing that, sometimes, the resources available and their coordination and organization are not enough and not sufficiently adjusted for the new challenges brought on by global warming and the Portuguese desertification of the interior and the consequent land and agricultural abandonment in these zones.

These results urgently call for public policies that promote cooperation among the Portuguese municipalities in the problematic issues related with fire. This could be done, for example, through public funds for forest management targeted at groups of neighbouring municipalities, where the main objective is to bring together the municipalities in the definition of common strategies for forest and land planning or management. On the other hand, it is important to optimize resources, promote training and provide better coordination of the human resources available, in order to improve their efficiency, namely in situations of extreme occurrences. Again, cooperation with neighbouring municipalities is important, because some which possess good strategies and coordination may be considered as benchmarks.

9 Final remarks

Both fires and the plague of the nematode are two of the most problematic sources of destruction in Portuguese forests. Forestry and wine production are two interesting agrarian activities, considered as economic clusters, that bring important dynamics, namely in the rural regions of Portugal. It is important to preserve the Portuguese forest and the studies, namely those related with the development of new instruments and new methods of support for the design of innovative policies, which are a fundamental contribution towards reducing the suffering and the damage to populations, specifically to those that live close to forest areas.

This study enables one to observe clusters of municipalities with more wildfires and burnt area incidence which are spatially auto correlated. In these areas, it is important that the involved municipalities cooperate in strategies to prevent and fight forest fires. In fact, inside each cluster with spatial autocorrelation for high values the objective is common and these actions may spread to neighbouring municipalities. On the other hand, it is important that the central, national and European institutions design similar policies and give incentive towards the cooperation among municipalities, because, in general, the dynamics and the causes will be similar, whilst not forgetting local specificities.

It will be important that in future studies this work will have continuity, namely through a local perception of the involved municipalities, in the clusters found, about what is actually being done in common and about the perspective of creating together more effective strategies towards preventing and fighting wildfires. In fact, even for the design of policies by public institutions it is very important to understand the perception of the several operators related with the destination of the different instruments of policy.

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Vítor João Pereira Domingues Martinho has a Ph.D. in Economics from the University of Coimbra, Portugal, is Coordinator Professor with Aggregation in the Polytechnic Institute of Viseu, Portugal, and is Guest Professor in the University of Trás-os-Montes and Alto Douro, Portugal.

Affiliations

Vítor João Pereira Domingues Martinho[1]

1 Agricultural School, Polytechnic Institute of Viseu, 3500 Viseu, Portugal