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Examining socioeconomic factors associated with wildfire occurrence and burned area in Galicia (Spain) using spatial and temporal data

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Abstract

Background The Spanish region of Galicia is one of the most fire-prone areas in Europe. Most wildfires are directly or indirectly related to human activities, suggesting that socioeconomic factors likely can inform wildfire management. Socioeconomic factors, for example, could help explain the causes and distribution of wildfires spatially and temporally within the region. We sought to examine how socioeconomic and biophysical variables and their fluctuations over time (2000–2015) might influence wildfire ignitions and hectares burned in Galicia using municipality-level data describing socioeconomic factors and forest land wildfires.

Results We used cluster analysis to characterize socioeconomic variation in our data set and regression analysis of panel data to investigate jointly the temporal and spatial dimensions of correlation between socioeconomic factors and wildfires. Using cluster analysis, we divided the region inter-territorially according to socioeconomic characteristics. Clustering divisions were found to have a similar pattern to that of Galician provinces. Our regression models for each cluster indicate that several socioeconomic factors are at least correlated with and may tend to influence wildfire occurrence and burned area in Galicia. We also found discernible patterns related to our identified clusters, confirming that differences between territories exist regarding the likely influence of socioeconomic factors on the number of wildfire ignitions and hectares burned.

Conclusions Results suggest that socioeconomic factors are as crucial as meteorological variables for understanding wildfire ignitions and burned area in Galicia (Spain). Accurate knowledge of inter-territorial socioeconomic differences could help public officials and forest managers to design wildfire prevention policies best suited to the socioeconomic, cultural, and environmental circumstances of each territory.

Keywords Wildfires, Socioeconomic determinants, Cluster analysis, Panel data analysis, Galicia, Spain, Wildfire prevention policies

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Resumen

Antecedentes La región española de Galicia es una de las áreas más proclives al fuego en Europa. La mayoría de los incendios forestales están directa o indirectamente relacionados con actividades humanas, lo que sugiere que un mayor conocimiento de determinados factores socioeconómicos podría dar pistas para la gestión de incendios. Los factores socio-ecológicos, por ejemplo, pueden ayudar a explicar las causas y distribución espacial y temporal de los incendios dentro de la región. Decidimos examinar cómo las variables socioeconómicas y biofísicas y sus fluctuaciones en el tiempo (2000–2015), podrían influenciar las igniciones y hectáreas quemadas en Galicia usando datos a nivel municipal que describen los factores socioeconómicos e incendios forestales.

Resultados Usamos análisis de clúster para caracterizar las variaciones socioeconómicas en nuestro conjunto de datos, y análisis de regresión con datos de panel para investigar de manera conjunta las dimensiones espaciales y temporales entre los factores socioeconómicos y los incendios. Dividimos la región de manera interterritorial de acuerdo a condiciones socioeconómicas con características similares. Se encontró que las divisiones en clústeres mostraban un patrón similar al de las provincias de Galicia. Nuestros modelos de regresión para cada clúster indicaron que diversos factores socio-ecológicos están al menos correlacionados con, y pueden tender a influir en, la ocurrencia de incendios y el área quemada en Galicia. Encontramos también patrones discernibles relacionados con los clústeres identificados, confirmando que las diferencias entre territorios existen en relación con la probable influencia de los factores socio-ecológicos sobre el número de igniciones y hectáreas quemadas.

Conclusiones Nuestros resultados sugieren que los factores socioeconómicos son tan relevantes como las variables meteorológicas para entender las igniciones y área quemada en Galicia (España). El conocimiento preciso de las diferencias socioeconómicas interterritoriales puede ayudar a los gestores públicos y de bosques a diseñar planes de prevención de incendios que se ajusten de la mejor manera a las circunstancias socioeconómicas, culturales y ambientales de cada territorio.

Background

Wildfires are a significant natural hazard that affected nearly 178,000 hectares of European land and forests in varying ecosystems in just 2018 alone (Jiménez-Ruano et al. 2017; Molina-Terrén et al. 2019; San-Miguel-Ayanz et al. 2019). Effective management of risks associated with potential wildfires depends on managers understanding the many factors and processes that influence wildfire occurrence and behavior before, during, or following wildfire events. Such information is of great importance for ensuring safety and minimizing negative effects for communities where wildfires occur (Bowman et al. 2019; Mancini et al. 2018; McCaffrey et al. 2013), as well as accurately anticipating potential future wildfire risks (Mansuy et al. 2019; Michetti & Pinar 2013; Moreno et al. 2014).

Although the influence of biophysical factors, such as topography, vegetation, and climate, has received significant research attention in the wildfire research literature, the potential role of human factors can be fundamental in different fire regimes because of their possible influence on wildfire ignitions, area burned, and fire severity and intensity (Moritz et al. 2014). In many regions, humans account for most wildfire ignitions and burned areas (McLauchlan et al. 2020; Prestemon et al. 2013). Furthermore, the characteristics and status of the human population can significantly influence the vulnerability of human populations to wildfire in any given location.

Natural hazards research literature suggests that vulnerability to wildfire is determined in part by the capacity of people to avoid or anticipate, cope with, resist and recover from the impact of a natural hazard (Wisner 2016). Different social, economic, political, and cultural factors can determine the vulnerability situation (Alexander 2013). In turn, existing vulnerability can be a significant factor in human-caused wildfires (Michetti & Pinar 2013; de Diego et al., 2019). Disentangling the influence of socioeconomic (human) factors from biophysical (natural) factors in wildfire ignition and behavior can help public officials and forest managers evaluate wildfire risks and identify potential policy and management approaches for addressing risks in different locations (Cattau et al. 2020).

Each year, European Mediterranean countries account for 85% of the total burned area in Europe (San-Miguel-Ayanz & Camia 2010). Between 2006 and 2010, 96% of forest fires in the Mediterranean region were directly or indirectly related to human causes (Ganteaume et al. 2013). Some explanatory factors included a decrease in farming or pastoral activities associated with socioeconomic development (Moreira et al. 2011), increased mobility of people, increases in tourism and recreational activities (San-Miguel-Ayanz et al. 2017), and traditional uses of fire as a management tool in agriculture, silviculture, and livestock breeding (Rodríguez-Vicente & Marey-Pérez 2010).

Spain is one of the Mediterranean countries that experience the greatest number of wildfires, and the Autonomous Community of Galicia, situated in the Northwest of the country, is the area in Spain most affected by wildfires. It is also one of the most affected regions in Europe (Montiel Molina & Galiana-Martín, 2016). The region experienced the highest number of forest fires between 2001 and 2010, with a total burned area equivalent to 42% of the entire country (Arellano-Pérez et al. 2018; MAPA 2012).

Appendix 1 provides a map of the region, for a better location; it also shows the historical evolution of hectares burned and number of wildfires in Galicia compared to Spain for the period 2001–2015 and illustrates how Galician wildfires have a significant weight in the general statistics of Spain.

Galicia comprises 2,060,453 hectares of forest, accounting for 69% of all land in the region. Forest lands are almost exclusively (97%) under private ownership and comprised of small forest parcels, agricultural operations, and livestock farms, totaling around 700,000 small proprietors (Bruña-García & Marey-Pérez 2018). The region has been affected by rural abandonment and a pronounced decline in population in recent decades (Rodríguez-Vicente & Marey-Pérez 2010).

Due to climate change, the annual period of meteorological danger in the region has become longer and more diffuse, with a less marked seasonality. This fact, together with the greater extension and quantity of forest fuel from abandoned lands, has led to an increase in the intensity of fires, their potential impact, and the difficulty of extinguishing them (Vega & Fernández 2020).

Galicia provides a valuable study area for examining human factors in wildfire occurrence and behavior because many socioeconomic characteristics prevalent there are often found to be associated with vulnerability to natural hazards and thus wildfires. Recent research (Birkmann 2013; FAAS, 2016) has tended to categorize these various factors into three primary dimensions:

- Land and environment: including meteorological variables (temperature, humidity, and wind velocity) and land-management-related variables (cattle/livestock farms, rustic lands, and infrastructures).
- Population: Focusing on demographic variables, such as the vegetative balance, the number of foreigners, and the aging of the population; and socioeconomic variables, such as the retirement and unemployment rates.
- Economy: Considering variables that measure wealth, such as per capita income or gross domestic product (GDP).

These three categories present a synergic interdependence. For example, population numbers largely depend on

land and economic characteristics, but in turn, the population can influence both land uses and the economy (Adger 2006). Consequently, interactions and interdependencies between climate, fire, people, and vegetation can change over time, along with the effect each of these factors can have on fire regimes in different locations (Archibald 2016). In sum, the causes and distribution of forest fires differ among countries and may also vary spatially and temporally within the same country (Calviño-Cancela et al. 2017).

We sought to examine the possible relationships between biophysical and socioeconomic factors, and wildfire ignitions and hectares burned in the region of Galicia. We sought to understand these effects by using the minimal area unit of analysis having similar characteristics (Prestemon et al. 2013). In the case of Galicia, this was the “municipality.” In Galicia, municipalities are minor geographical sections for which readily available information on socioeconomic factors and forest land wildfires are available. In addition, to identify inter-territorial differences in fire behavior in the region, we identified different groups of municipalities that share similar socioeconomic characteristics. Such information can help in designing risk mitigation policies best suited to each region’s socioeconomic, cultural, and environmental circumstances (Coughlan et al. 2019; Ganteaume et al. 2013).

Methods

We examined the potential influence of socioeconomic and biophysical variables on wildfire occurrence and area burned in the 314 Galician municipalities from 2001 to 2015. We obtained fire data, including fire frequency and size, from a database developed by the Spanish General Statistics on Forest Fires (EGIF)¹ and provided by the Ministry of Agriculture and Fisheries, Food and Environment (MAPAMA). Our analysis extended previous research, examining the potential influence of socioeconomic variables on fires in Galicia. In de Diego et al. (2019), we characterized the socioeconomic context of Galician fires. In de Diego et al. (2020), we conducted a detailed review of wildfire research literature, concluding that determining factors potentially could be grouped into three dimensions: environmental or territorial, social (population), and economic. In a third paper, we used panel data characterizing these dimensions for the Galicia region (de Diego et al. 2021). In this paper, we structure our analysis by focusing on 19 variables grouped into the abovementioned three dimensions (Table 1): land and environment, population, and economy.

¹ <https://www.miteco.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/incendios-forestales.aspx>

Table 1 Variables examined for their association with wildfires in Galicia

Land and environment	Wind-Summer	Wind velocity during summer
	Humidity-Summer	Humidity during summer
	T°-Summer	Temperature during summer
	DisCenter	Buildings and dwellings of a singular entity divided by a set of towns with less than ten buildings, which form streets, squares, or other urban roads
	Rural-hotels	Rural hotels per municipality
	%Bush-Pasture	Proportion of bush and pasture per municipality
	%Forest-tree	Proportion of tree forests per municipality
	%Livestock-farm	Percentage of cattle heads per farm
	Road-density	Road km per municipality
	Vegetative-balance	Difference between the numbers of births and deaths per municipality
Population	Waste-habitant	Waste produced per habitant per year
	%Unemployment	Population temporarily off per municipality
	%Foreign	Percentage of foreigners per municipality
	Population > 64	Population over 64 per municipality
	Retirement-pensions	Number of retirement pensions per municipality
Economy	PlotValue-habitant	Plots in thousands of Euros divided by people registered in the Real Estate Cadastre
	GDP-per-capita	GDP per person
	Income-per-capita	Income per person
	Debt-per-capita	Municipality debt per person

de Diego et al., 2020 and 2021

Information for developing our environmental variables was obtained from the Nature Data Bank (BDN)² and Meteogalicia.³ Information for developing our socio-economic variables was obtained directly from the existing statistical information for each of the municipalities in the region through the Galician Institute of Statistics (IGE).⁴ We chose municipalities as the observational unit since they are the smallest entity for information on wildfires and the minor territorial division for which accurate and consistent socioeconomic data are available.

A graph of this methodological process is provided in Appendix 2.

We used cluster analysis to identify potential inter-territorial differences across our study area. Cluster analysis often is used to classify observations into relative groups (or clusters). We used cluster analysis to group Galician municipalities with similar biophysical and socioeconomic characteristics. We employed dendrogram criteria (Kaufman & Rousseeuw 2009) to create the minimum number of clusters with sufficient information. This resulted in four identified clusters. We also explored possible relations between those clusters and their distribution by province.

We used factor analysis as a preliminary step to the cluster analysis to reduce the 19 variables we had at the outset into a fewer general “factors,” based on the maximum common variance for all variables that can then be translated into a common factor score. This factor score can be used as an index of all variables for further analysis. We conducted the factor analysis on the 19 variables by taking an average of the mean values across the 15 years of data in hand. We then applied cluster analysis to the factor scores (standardized, mean 0, and standard deviation 1).

Panel data models can be useful when applied to cross-sectional spanning long time periods, enabling examination of changes over time. We estimated panel regression models to identify and examine potential correlations with 18⁵ selected explanatory variables (annual means) with past wildfires in the four territories identified by the combined factor and cluster analysis. The dependent variables examined included the number of wildfires and area burned, consistent with previous wildfire research (Amatulli et al. 2007; Boubeta et al. 2019; Leone et al. 2003; McLauchlan et al. 2020; Turco et al. 2019). Using these two dependent variables, we estimated four regression models corresponding to the four territories obtained from the cluster analysis. Robust

² <https://www.miteco.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/default.aspx>

³ <https://www.meteogalicia.gal/web/inicio.action>

⁴ <https://www.ige.eu/web/index.jsp?paxina=001&idioma=es>

⁵ One variable was removed to achieve a better fit of the model.

Table 2 Factor loadings

Variable	Factor1 Aging	Factor2 Meteo	Factor3 Deprivation	Factor4 Wealth	Factor5 Forest	Factor6 Pop Density	Factor7 Tourism	Factor 8 Debt	Uniqueness
Plot value-habitant	− 0.8882								0.1787
%Foreign	0.8788								0.1585
Population > 64	0.7315								0.1669
%Livestock-farm	− 0.6906								0.2832
Retirement-pension	0.5200								0.2692
Humidity-summer		0.9510							0.0906
Temperature-summer		− 0.9364							0.1215
Wind-summer		0.8851							0.2069
%Unemployment			0.8624						0.2113
Waste-habitant			0.8415						0.2591
GDP-per-capita				0.8428					0.2316
Income-per-capita				0.6888					0.2701
DisCenter									0.4603
%Bush-pasture					− 0.8011				0.2542
%Forest-tree					0.7898				0.2948
Vegetative-balance						− 0.7802			0.2847
Road-density						0.5869			0.2716
Rural-hotels							0.8276		0.3071
Debt-per-capita								0.9638	0.0478

KMO 0.674; Bartlett (χ^2 2430.876, p value = 0.000); percentage variance explained 77.01%

standard deviations were used to solve the heteroscedasticity problems (ordinary least squares estimators are not optimized) and to allow for a correct inference on the β calculation. Logarithms were taken when necessary; the standard errors were estimated by conventional method and clustered by municipality and year. There are no problems of multicollinearity (see VIF in Tables 5 and 6). The software STATA-16 (StataCorp., 2019) was used to run the different models, establishing the data as cross-sections of individuals observed over time. We selected this software as it is the most suitable for panel-data methodology.

Estimating a single panel data model including data from all four territories for each of the two equations examining the two dependent variables likely would have enhanced the statistical significance of the independent variables, as there was greater variability in the data associated with these dependent variables. However, previous literature suggests the existence of intra-regional differences according to the characteristics of the different Galician territories, v.g. land uses (Corbelle Rico & Crecente Maseda 2014) or pyromaniac behavior (Chas-Amil et al. 2010). In this paper, we have used the cluster to obtain homogeneous units (based on socio-economic causes rather than geopolitical issues) on which to perform the panel analysis.

We chose to use a fixed-effect model based on the contrast of Hausman (significant in all clusters for number of wildfires and in clusters 1 and 2 for hectares burned as showed in Tables 5 and 6) which demonstrated that the fixed effects model, in this case, provided a better fit than a random effects model. Fixed effect panel data models identify the effects of explanatory variables based on within-municipality variation, while random panel data models assume that the overall effect of omitted variables is randomly distributed over time and municipalities and is therefore uncorrelated with other explanatory variables.

Results

Factor and cluster analysis

Our factor analysis (Table 2) resulted in eight factors which we characterized as follows:

- Factor 1 “Aging”: This was positively correlated with the population over 64 years of age, retirement pensions, and the percent of foreigners, and negatively correlated with aging pasture lands, which are increasingly being abandoned in the study area. Their employment can explain the presence of foreigners in the elderly care sector or their occupying of low-price lands.

- Factor 2 “Meteorology”: Included variables describing temperature, humidity, and wind velocity. The relation between temperature and humidity and wind velocity is inverse. Therefore, low temperatures usually mean high humidity levels and increased wind velocity.
- Factor 3 “Deprivation”: Represented the relationship between unemployment and waste production per person. A higher population density implies a higher unemployment rate. Also, a larger population generates a more significant waste accumulation (Jímenez & Medina 2001).
- Factor 4 “Wealth”: Represented by GDP and income. These variables are strongly related in that municipalities with high GDP also tend to have high incomes per capita.
- Factor 5 “Forest”: related to the physiognomy of land. It has a positive correlation with the wooded territory and a negative correlation with bush and pasture lands.
- Factor 6 “Population density”: Represented the relationship between an increase in population (positive vegetative balance) and higher road densities. Generally, more populated areas tend to have more excellent road and infrastructure networks, which can influence the prevalence of wildland-urban interface, which account for a high percentage of wildfires (Coughlan et al. 2019)
- Factor 7 “Tourism”: Included rural hotel infrastructure, showcasing the increasing importance of the tourism sector in the region from both the ecological and the economic points of view.
- Factor 8 “Debt”: Addressed the economic situation of different municipalities. Those municipalities with high levels of debt usually face more direct economic conditions.

Together, these factors align with the dimensions of Land, Population, and Economy themes as we have previously labeled them (Table 3).

Table 4 and Fig. 1 show factor scores for each cluster of observation units (municipalities). Figure 2 is a visual of the geographical distribution of the clusters. As we can see in Fig. 2, each municipality can belong to one cluster, and there is an explicit geographical distribution pattern: municipalities belonging to cluster 1 are more prevalent in the Galician Northwest, whereas cluster 2 is most prevalent in the Southwest, cluster 3 in the Southeast, and cluster 4 in the Northeast. To confirm this distribution, we examined the relation between the clusters and the Galician provinces using Chi and Cramér’s V tests (p -value = 0.000/Cramér’s

Table 3 Relation between factors and dimensions

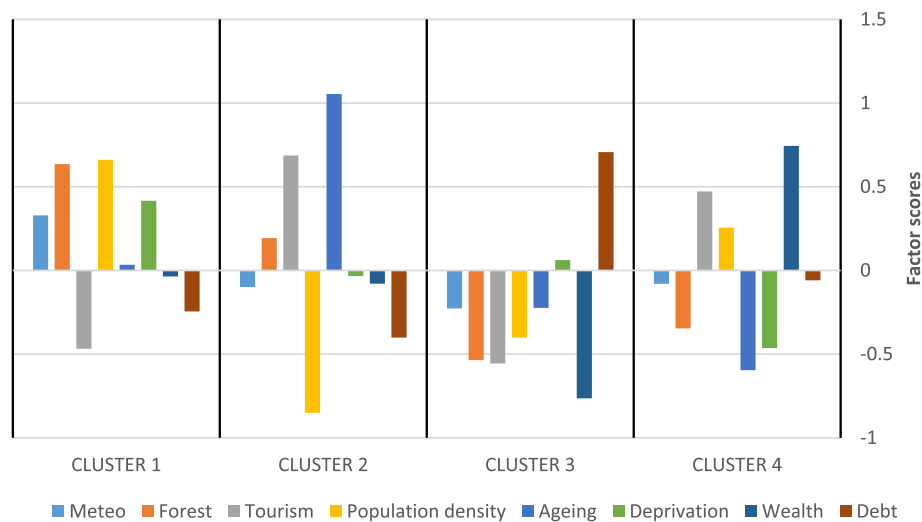
Variable	Factor	Dimension (according to literature)
Humidity-summer	Meteo	Land and environment
Temperature-summer		
Wind-summer		
Rural-hotels	Tourism	Population
%Bush-pasture	Forest	
%Forest-tree		
Vegetative-balance	Population density	Population
Waste-habitant	Deprivation	
%Unemployment		
%Foreign	Aging	Economy
Population > 64		
Retirement-pension		
GDP-per-capita	Wealth	Economy
Income-per-capita		
Debt-per-capita	Debt	

$V=0.4603$) (Heumann and Shomaker, 2016). Our results of both tests suggest that the geographical distribution of the municipalities belonging to the four clusters has a similar pattern to that of the Galician provinces: cluster 1, NW, A Coruña; cluster 2, SW, Pontevedra; cluster 3, SE, Ourense; and cluster 4, NE, Lugo.

- Cluster 1 (Northwest): Encompassing 29% of the municipalities, the Northwest cluster is mainly located in the Galician NW, although some municipalities can be found near the region’s center. Climate variables are especially relevant in this cluster for two reasons: (1) the proximity of the whole area to the sea and (2) the predominance of forestry areas over pasture lands. Three important Galician cities are located in this cluster—A Coruña, Santiago de Compostela, and Ourense. These cities all have relatively high population densities, which inevitably implies high unemployment rates due to structural and frictional unemployment. Still, their relative prosperity relative to rural areas has resulted in reasonably low debt rates. As far as the risks of wildfires are concerned, the Northwest region could be affected by accidental fires related to wildland-urban interface and to ill-managed forest areas (Table 4).
- Cluster 2 (Southwest): Including 20% of Galician municipalities, the Southwest cluster mainly comprises unpopulated areas (forest areas) dedicated to rural tourism, except for the two urban cores in the cluster: Pontevedra and Vigo. The Southwest cluster

Table 4 Cluster distribution

Dimensions	Factors	Clusters			
		Cluster 1	Cluster 2	Cluster 3	Cluster 4
Land and environment	Meteo	0.329	− 0.099	− 0.227	− 0.08
	Forest	0.635	0.193	− 0.536	− 0.346
	Tourism	− 0.468	0.687	− 0.556	0.472
Population	Population density	0.661	− 0.851	− 0.401	0.256
	Aging	0.034	1.054	− 0.224	− 0.596
	Deprivation	0.416	− 0.033	0.062	− 0.464
Economy	Wealth	− 0.036	− 0.079	− 0.764	0.744
	Debt	− 0.245	− 0.401	0.707	− 0.059
n/%		91/28.98	62/19.75	74/23.57	87/27.71

**Fig. 1** Cluster distribution graph

is characterized by relatively low population densities, an aging population, and low unemployment rates. Its reasonably good economic situation can be linked to the prosperity of the region's urban centers and the two-decade-long rural tourism boom.

- Cluster 3 (Southeast): With 24% of Galician municipalities, the Southeast cluster is mainly comprised of depopulated areas and abandoned pasture lands, with a scarce presence of the tourist sector. There are no essential urban centers. Southeast municipalities have the lowest income, and the highest debt rate of the four clusters studied. This situation and the peculiarities of the climate variables (low wind, low humidity, high temperatures) could potentially be associated with human-caused fire risks.
- Cluster 4 (Northeast): 28% of Galician municipalities belong to the Northeast cluster, mainly those of the NE of the region and some toward the center. There

is only one urban core to speak of, Lugo, with the rest of the region being relatively sparsely populated and rural and dedicated to pasture lands and agrotourism. Its high per capita income and low debt ratio explain the economic prosperity that the Northeast cluster enjoys (Table 4).

Panel regression models

Our regression models for each territory cluster indicate that several socioeconomic factors are at least correlated with and may tend to influence wildfire occurrence and burned area in Galicia. We found discernible patterns related to our identified clusters, confirming that differences between territories likely exist regarding the potential influence of socioeconomic factors on the number of wildfire ignitions and hectares burned.

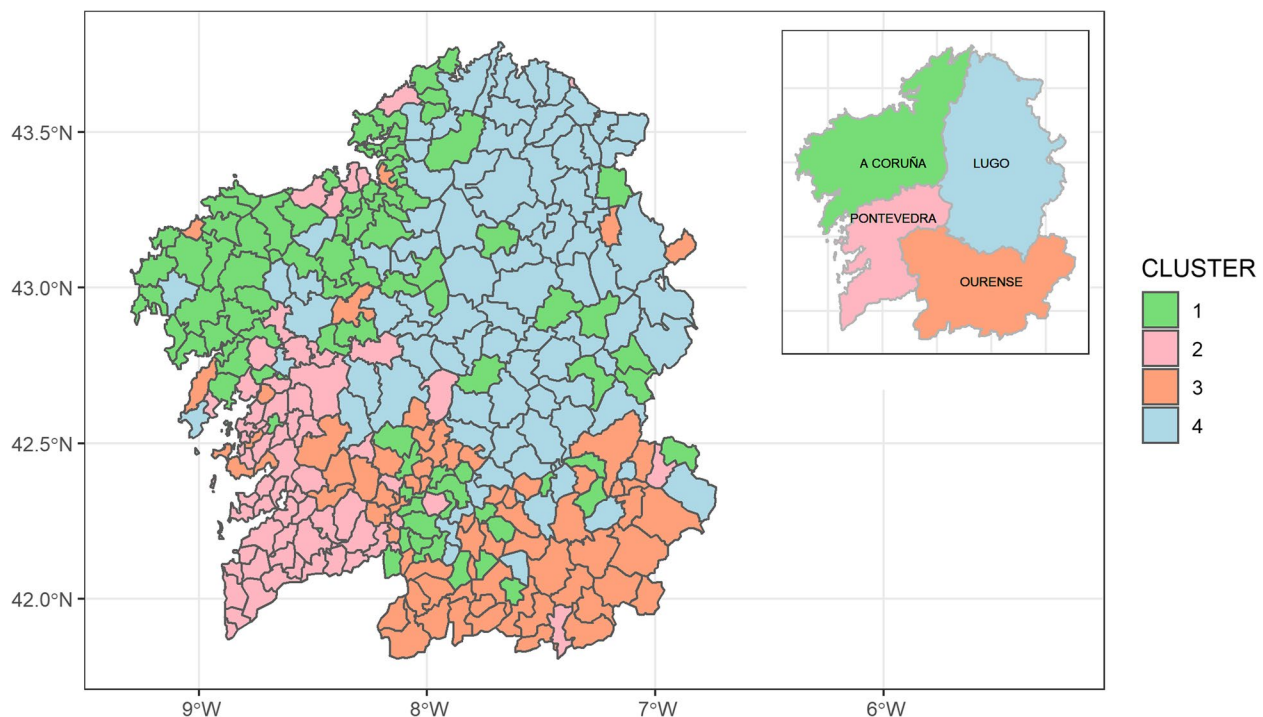


Fig. 2 Cluster distribution map

Number of wildfires

The Northwest (cluster 1) is characterized by the effects of land-related, meteorological, and economic variables over the number of ignitions and, most notably, by the inverse relation linking the variables bush/pasture and forest on the number of wildfires. Therefore, the low number of fires is connected to the predominance of forest areas and the existence of big cities with a greater wildland-urban interface. Abandoned or ill-managed shrublands tend to be more prone to fires (Calviño-Cancela et al. 2017). The relative prosperity of those cities (A Coruña, Santiago de Compostela, and Ourense) likely leads to our economic variables seemingly having little effect on the number of wildfires (Table 5). Even so, the model shows some evidence of how economic deprivation can influence the human origin of wildfires. Indeed, the number of wildfires has a positive relation to the number of pensioners and is inversely associated with income per capita. Conceivably, disadvantaged homes with various members receiving government aid could be enlisted in efforts to mitigate or extinguish fires if such activities were offered as an additional income source. The hypothesis of the human origin of ignitions can also be reinforced by the contradictory behavior of the variables related to the climate in this sub-region. On the one hand, the negative relation between wildfires and

humidity seems to make sense, as drought-strike lands show a higher propensity for fires. On the other hand, as forests are naturally prone to wildfires when temperatures rise, the inverse relationship between temperature and wildfires could reinforce the human source of ignitions.

The Southwest (cluster 2) is characterized by the coexistence of unpopulated areas and prosperous cities. The behavior of land-related variables (negative impact of abandoned pasture lands and the lack of forests) is similar to that of Southwest but reinforced by the effect of the decrease in livestock farms as an additional factor in the degradation of pasture lands that, abandoned, become shrub-lands (Lasanta et al. 2019) (Table 5). In other words, Southwest fires are caused more by climate conditions (drought brought on by low humidity) and their effect on neglected or abandoned areas. This is indicated by the negative values of the variables rural hotels, livestock farms, and unemployment (the inverse relationship between the unemployment rate and the number of fires can be explained because unemployment is concentrated in urban centers). This also is indicated by the positive coefficient for retirement pensions, such that there seems to be a positive relationship between the number of fires and the number of pensioners living in deprived areas. The positive relationship between lower temperatures, low wind velocity, and wildfire occurrence

Table 5 Number of wildfires panel data models

Dimension	VIF	N° Wildfires	Cluster 1 Northwest Coef	Cluster 2 Southwest Coef	Clusters 3 Southeast Coef	Cluster 4 Northeast Coef
Land and environment	1.35	Wind-summer	-.01183	-.03009**	.02118	.00399
	1.23	Humidity-summer	-.00984***	-.01433***	-.00918***	-.00458*
	1.09	Temperature-summer	-.01582**	-.01344*	-.01777***	-.00254
	1.04	LnDisCenter	.15547	-.14,103	-.11133	.25372
	1.06	Ln Rural-hotels	-.21279*	-.19625*	-.37618***	-.07725
	1.91	Ln %Bush-pasture	-.15,933***	-.66432	-.58266	.2535
	1.39	%Forest-tree	-.10,168***	-.85,549***	-.29113	-.64,757***
	1.30	Ln %Livestock-farm	-.08887	-.19342	-.24270***	-.73732***
	1.84	Ln Road-density	-.0021	-.23780	-.64574***	.62055
Population	1.14	Ln Vegetative-balance	.00103	-.00014	-.0013	.00062
	2.20	Ln Waste-habitant	.10676	.00301	-.0045	.00509
	1.07	Ln %Unemployment	-.11372	-.34137**	-.43534***	.17234
	1.07	Ln %Foreign	-.07457	-.15793*	-.06604	-.04223
Economy	1.69	Ln Retirement-pension	.73193***	.50857**	.30486***	.20861
	1.10	Ln PlotValue-habitant	-.0321	-.05571	.06689	-.10407
	1.20	Ln GDP-per-capita	.3546	-.33950	-.17,156***	-.12,344***
	1.17	Ln Income-per-capita	-.00007***	-.00001	-.9.51e-06	-.00008***
	1.23	Ln Debt-per-capita	.00380	.00271	-.05532**	-.08246***
		_cons	14,343***	10,754**	92,605**	11,345***
		n/Obs (n*years)	91/ 1,365	62/930	74/ 1,110	87/ 1,305
		R ²	within = 0.2946 between = 0.0545 overall = 0.0114	within = 0.3795 between = 0.0381 overall = 0.0014	within = 0.3368 between = 0.0026 overall = 0.0061	within = 0.2831 between = 0.1708 overall = 0.1642
		Hausman	$\chi^2 = 135.99$ ***	$\chi^2 = 24.20$ ***	$\chi^2 = 41.65$ ***	$\chi^2 = 24.20$ ***

Note: *p* value < 0.01*; < 0.05**; < 0.01***

seemingly reinforces the hypothesis of human sources of the ignitions.

In the Southeast (cluster 3), which comprises significantly deprived and depopulated areas, all of the examined dimensions (climatological, land-related, population, and economic dimensions) contribute to explaining the human origin of wildfire ignitions (Table 5). Although results for the land-related and environmental variables are similar to those for the other clusters, there seemingly is a higher and more significant direct effect of the economic and population variables on wildfires. Fires in this region are caused mainly by climate conditions (drought brought on by low humidity and high wind speeds) and their impact on neglected or abandoned areas inhabited by a decreasing number of aging, low-income populations. This is shown by the negative coefficients for the variables rural hotels, livestock farms, unemployment rate, GDP, and the positive coefficient for the variable retirement pensions. The influence of deprivation on fire occurrence is further indicated by the negative coefficient for the variable debt per capita, possibly suggesting that

a low level of debt per capita also means a low level of investment in preventive actions and infrastructures.

The results for the Northeast (cluster 4), a mainly rural, prosperous, and scarcely populated region dedicated to pasture lands and agrotourism, corroborate previous findings. The lesser impact of land-related and environmental variables in wildfire occurrence can be explained by the greater importance given in the region to the conservation of the environment, which positively impacts its economy (Table 5). Economic variables associated with poverty (low GDP, low income) and deprivation (low investment in fire prevention or infrastructure) may help explain the human origin of wildfires in this area.

In short, the human causes of wildfires in Galicia are reinforced by the contradictory relationship between temperature (low) and humidity (low). According to the results of our estimated regression models, rural abandonment, neglect of the environment, aging, deprivation, and insufficient investment in prevention and infrastructure turn out to be the main factors correlated with wildfire ignitions.

Table 6 Hectares burned panel data model

Dimension	VIF	Ha Burned	Cluster 1 Northwest Coef	Cluster 2 Southwest Coef	Clusters 3 Southeast Coef	Cluster 4 Northeast Coef
Land and environment	1.35	Wind-summer	−.02801	−.0605824**	.0669***	.04468**
	1.23	Humidity-summer	−.00223	−.01431***	−.00738*	.00708*
	1.09	Temperature-summer	−.00004	.00189	−.00805	.01912*
	1.04	Ln DisCenter	.17163	−.3179	−.25961**	.03178
	1.06	Ln Rural-hotels	−.20130	−.31360	−.51579	−.03847
	1.91	Ln %Bush-pasture	−30,286***	−34,749**	−28,869***	−.34483
	1.39	%Forest-tree	−15,550***	−16,052***	−64,288	−95,839*
	1.30	Ln %Livestock-farm	−.28676*	−.56377***	−.25846**	−.86850**
	1.84	Ln Road-density	.21189***	−.01169	−17,110***	−.36098
Population	1.14	Ln Vegetative-balance	.00039	−.00132	.00184	.00066
	2.20	Ln Waste-habitant	.03017	.05754	.02610	.02302
	1.07	Ln %Unemployment	.12995	.14741	.09595	.01529
	1.07	Ln %Foreign	−.12844	−.22934	−.2812***	−.14476**
	1.69	Ln Retirement-pension	.85544**	.76612	.78235***	.02389
Economy	1.10	Ln PlotValue-habitant	−.16374**	−.12050	−.37516***	−.30552
	1.20	Ln GDP-per-capita	.10595	−15,639**	−23,881***	−21,871***
	1.17	Ln Income-per-capita	−.0001***	.00002	.00002	−.00009**
	1.23	Ln Debt-per-capita	.02321	.01553	−.12473**	−.06769
		_cons	25,309***	33,277***	21,167***	1,518,622
		n/obs (n*years)	91/ 1.365	62/930	74 / 1.110	87 / 1.305
		R ²	within = 0.1537	within = 0.1936	within = 0.1594	within = 0.1115
			between = 0.2560	between = 0.3876	between = 0.2056	between = 0.0618
			overall = 0.0693	overall = 0.0958	overall = 0.0709	overall = 0.0490
		Hausman	$\chi^2 = 24.70$ *	$\chi^2 = 18.95$ *	$\chi^2 = 13.90$	$\chi^2 = 7.86$

Note: p value < 0.1*; < 0.05**; < 0.01***

Hectares burned

For Northwest municipalities, the number of hectares burned appears to depend on the abandonment of the land rather than on the variables associated with climate, as shown by the negative value of the coefficients for the variables describing proportion of forest, brush, and pasture and number of livestock farms (Table 6). The presence of large cities in the Northwest suggests the importance of some economy and population variables in Wildfire occurrence, shown by the negative values of the coefficients for variables such as plot value and income per capita and by the positive value of the variable Retirement pensions. Although similar to the Northwest, the Southwest presents a stronger connection between the number of hectares burned and land-related and climate variables and a weaker effect of the Population and Economic variables. This can be explained by the absence of big cities in the Southwest and the presence of a more significant number of abandoned, unpopulated areas.

The Southeast cluster is one of the most fire-stricken areas in Galicia. Here, land and environmental variables are as important as those related to the population and

the economy (Table 6). These results reflect the socio-economic vulnerability of this low-income area. Depopulated dress with abandoned pasture lands results in an adverse effect on the land-related variables, shown by a higher percentage of shrub lands and a low rate of livestock per farm. Climate variables demonstrate the direct effect of wind velocity and the inverse effect of humidity over the spread of wildfires. The negative relation between the number of foreigners and the number of hectares burned deserves special attention: foreigners in Galicia live mainly in bigger urban centers, where they are employed in the elderly care sector, and thus their number is an indicator of urban prosperity.

In the Northeast cluster, climate variables (mainly wind velocity and temperature) appear to have a fairly significant influence on the number of hectares burned. In any case, wind velocity and temperature need to be considered together with those describing land abandonment (a decreasing number of livestock farms results in larger shrub-land areas) and precarious economic conditions (lower GDP and income per capita). As in the Southeast, the low number of foreigners indicates that the Northeast

population live in larger cities, where they are employed in the elderly care sector.

In terms of the number of hectares burned, explanatory variables related to land use and climatological conditions seem to result in stronger relationships than other explanatory variables examined. Indeed, we found that economic and population variables were not strong predictors of the sizes of wildfires. Still, our analysis shows that social variables have more to do with the causes of fires than with their consequences. The influence of economic and population variables was most substantial in the Southeast regarding hectares burned. Its difference in this respect from the other territorial clusters examined likely stems from the economic and population characteristics explained above.

Discussion

We sought to improve understanding of forest land wildfires in Galicia by examining the potential influence of socioeconomic and biophysical variables on wildfire occurrence (ignitions) and hectares burned over the 2001–2015 period. We used clustering to analyze the spatial dimension and regression analysis of panel data to investigate the fluctuation of variables over time. The cluster analysis allowed us to divide the region interterritorially into four areas, according to its socio-economic behavior only. The panel data analysis showed rural abandonment, neglect of the environment, aging deprivation, and low investment in prevention and infrastructure as determinants of wildfire ignitions.

Recent wildfire research suggests a need for improved analyses of biophysical and socioeconomic factors in wildfire occurrence and area burned. Such analyses can aid policymakers and managers in understanding wildfire dynamics within regions and differences between territories (Costafreda-Aumedes et al. 2017; Ganteaume et al. 2013). Scholars have repeatedly used cluster analysis as an attempt to identify and characterize spatial patterns of fire regimes. In Spain, Moreno and Chuvieco (2013) describe four fire regimes in terms of the density and seasonality of fire activity, and Montiel and Molina (2016) identify five land-based fire scenarios—connecting fire regimes and territorial dynamics—on a national and regional scale. For Portugal, Parente et al. (2016) identify two types of fire regimes driven by climate and vegetation. Although the variables examined in past research to a greater extent have to do with climatic or biophysical factors, all authors agree on the importance of the human factor for better understanding fire regimes and optimizing fire risk mitigation policy measures.

The present study is in line with other works that have used the socioeconomic variables for spatial fire segmentation. In this regard, Chas-Amil et al. (2010) examined

the spatial distribution of human-induced fire risk attending to causes and underlying motivations associated with fire ignitions in Galicia. They found four distinctive types of municipalities according to the incidence of intentional agricultural-livestock fires, pyromaniacal behavior, negligence, and unknown causes. Gaither et al. (2011) examined the association between wildland fire risk and social vulnerability in six states in the US southeast and concluded that poorer communities in high wildfire risk areas may be more disadvantaged than more affluent communities in high fire-risk areas. Ferrara et al. (2019) demonstrated for the South of Italy that wildfire attributes (frequency, intensity, and severity) are systematically higher in socioeconomic contexts characterized by rural poverty, unemployment, and deregulated urban expansion. The findings from Sousa et al. (2021) confirm that mainland central Portugal has a low potentiality index—and the subsequent rural abandonment and lack of human activities, such as agriculture—which is one of the main factors facilitating fire spread in this region.

Like past studies, of the potential influence of socioeconomic factors on fire frequency and size at regional scales, we have relied on statistical and econometric approaches, including the use of panel data (Costafreda-Aumedes et al. 2017; Mercer & Prestemon 2005; Michetti & Pinar 2013; Padli et al. 2018) after segmenting our study area based on regional similarities in socioeconomic conditions using factor and cluster analyses. Factor analysis splits the data set of previously selected variables into various dimensions, demonstrating relationships between specific explanatory variables and the existence of different socioeconomic components (or factors). These factors, similar to the dimensions described in the relevant literature (Adger 2006; Chas-Amil et al. 2015; FAAS, 2016), allowed us to analyze fire data for each territory with greater precision. Also, cluster analysis made it possible to identify geographical differences within territories. These geographical differences can inform fire management, as the variables within the factors appear to influence the number of ignitions and hectares burned differently. Lastly, our two panel data sets enabled us to take advantage of both the spatial and temporal variation in fire and socioeconomic data.

The research timeframe used in our study is longer than that of other work related to Galicia—2001–2009 used by Barreal et al. (2011), 2006 used by Balsa-Barreiro and Hermosilla (2013), and 2001–2010 used by Loureiro and Barreal (2015). Only Prestemon et al. (2019) examined a slightly more extended period (16 years from 1999 to 2014). Regarding the unit of spatial analysis, some scholars have used smaller research units, such as parishes, to examine the influence of human variables on wildfire patterns (Chas-Amil et al. 2015). However, since parishes

are not considered as local entities (Ministerio de Política Territorial 2022), such macroeconomic variables that are measured at the municipal level and used in the models presented in this article, such as GDP, GDP per capita, and debt ratio, were not available at the parish level.

Concerning the dependent variable “Number of wildfires,” the importance of the land and environmental dimensions is remarkable. Ignitions appear to be related to an increase in available fuel load and, in turn, the existence of ill-managed lands (Moreira et al. 2011). The presence of farms and livestock has also been suggested as an explanation for ignitions in rural areas (Ganteaume et al. 2013). In this sense, our results confirm the potential relationship between these variables and the number of ignitions. In addition, together with the relevant literature, this paper has considered the aging of the rural population as a primary factor in ignitions through traditional fire-use practices (Grala et al. 2017). The seeming relationship between economic deprivation and ignitions prominent in the Southeast and Northeast (clusters 3 and 4) suggests that economic dimension variables play an important role in wildfire occurrence. Nevertheless, our results concerning the unemployment rate show contradictory findings. Mercer and Prestemon (2005) considered unemployment a proxy for economic activity, so there is a positive relationship between the number of ignitions and the unemployment rates. In our analysis, the negative relationship between unemployment and ignitions likely can be explained by the fact that our unemployment variable is part of the “Population” factor, and so contributed to describing the characteristics of urban centers where the number of ignitions is much lower.

As far as the dependent variable “Hectares burned” is concerned, the effects of the independent variables are slightly different, given that hectares burned is related to the fire’s behavior—specifically its intensity and spread (Calviño-Cancela et al. 2017). Past research suggests that hectares burned are affected mainly by land-related or biophysical factors, and less by economic and population variables (Balch et al. 2017). Our results corroborate previous findings, showing a significant influence of the meteorological and land-related variables in the hectares burned. The remarkable and positive relationship between road density and hectares burned can be explained by the importance of roads in the spread of a wildfire. This finding confirms results of previous research. In contrast, roads have also proven to help stop the spread of wildfires in some regions (Ganteaume et al. 2013). Additionally, as it has already been pointed out by other authors (Cattau et al. 2020; Grala et al. 2017), to better explain the characteristics of fire, it is still necessary to consider interactions between climate, land, and socioeconomic factors. This is reflected in our own results, where population and other socioeconomic characteristics are statistically significant.

In this respect, land abandonment—one of the main problems in rural areas in Galicia—seemingly directly affects the quantity of fuel available, as it increases the presence of shrubs and grassland, along with non-managed forest areas (Arellano-Pérez et al. 2018; Padli et al. 2018; Vega-García & Chuvieco 2006).

Improved knowledge of both temporal and spatial dimensions of wildfire determinants can be helpful for designing wildfire risk mitigation policies and management adapted to different regions (Costafreda-Aumedes et al. 2017; Oliveira et al. 2017). Chas-Amil et al. (2015) suggest that policies that incentivize cooperative forest management and constrain urban development in fire-prone wildlands could be used to reduce wildfire risk in Galicia. Canadas (2016) points out for a Portuguese case how the such legislation can have very different effects depending on the human variables for each region. Further, Blas and Lourenço (2019) show similar fire behavior for a Spanish-Portuguese forestry sector case.

Current legal regulation (*Ley 3/2007, de 9 de Abril, de Prevención y Defensa Contra Los Incendios Forestales de Galicia*, 2007), in force for 15 years and having undergone more than 80 modifications, has proven to be ineffective at reducing fires in Galicia. This Forest Fires prevention and defense law is more focused on suppression rather than risk mitigation by way of fire prevention. Moreover, it has generated an intricate political-administrative and territorial tangle, with the responsibility for preserving lands falling on a myriad of small landowners who cannot be identified by municipal authorities (Míguez Macho 2020). This, together with the existence of unsolved social tensions due to conflicting land uses, or the low level of effectiveness and organizational efficiency of firefighting services has made the goal of eradicating (or even reducing) the recurrent summer fires in the region fail (Pérez Vilariño, 2019). Despite all this, there is room for hope, as the drafting of a new Law began in October 2022. The new law likely will include a participatory process involving relevant stakeholders, including specialists, professionals, and policymakers (Osobodigital 2022). The underlying principles of this new law seem to be aligned with the results and conclusions of our research, as it focuses on pillars such as socio-demographic changes, preventive actions on the territory or the promotion of initiatives for the recovery of forest uses, “addressing the sensitization and awareness of citizens” (Xunta de Galicia 2022c). Reducing the number of wildfires becomes easier when there is better knowledge of their causes (Keeley & Syphard 2018) and all the relevant parties are involved (Madrigal Olmo 2020). In this respect, greater understanding of the region’s fire behavior provided by our study could contribute to improved design of the specific measures for applying this coming Law.

Conclusion

Although currently the public officials appear to be more focused on providing human and material means to prevent and mitigate the effects of wildfires, they are increasingly aware of the importance of changing social behavior to reduce the negative impact of wildfires (Xunta de Galicia 2022b). Indeed, recent applied research pinpoints that the most effective tool for fire prevention is the promotion of the sustainable management of natural resources (i.e., agriculture, extensive livestock farming, forest harvesting, preventive forestry, or prescribed burning) (Plana Bach et al. 2020).

In this vein, our study sought to contribute to forest land protection against wildfires by focusing on the human variables related to wildfires, from a twofold perspective: Firstly, we have provided broader knowledge of intra-regional differences regarding the production of wildfires. So different prevention and protection solutions should be applied to different contexts.

Secondly, we suggest that such information could aid in designing risk mitigation measures that consider the socioeconomic factors that likely influence wildfires. Specifically, these include the causes behind the ill-management of lands, such as land abandonment and non-managed forest-areas, as well as characteristics of the population itself, including aging, living in rural areas, using traditional burning practices, economic deprivation, and high unemployment rates.

We must, nevertheless, recognize that progress is being made (Xunta de Galicia 2022a). For example, many municipalities are developing local fire prevention plans and innovative approaches for promoting land use such as agro-forestry polygons, projects for common land use or projects of “model villages” (AGADER-Axencia Galega de Desenvolvemento Rural, *n.d.*; Corbelle-Rico et al. 2022).

Moreover, as highlighted by the Galician parliament (Boletín Oficial del Parlamento de Galicia 2018), fire-prevention, land-use planning, and rural-development policies should be coordinated but adapted to the peculiarities of the different territories of the region.

Our policy proposal, in this same line of action, would be to design measures of awareness-raising, dissemination, training, and promotion of sustainable environmental management practices that enhance the prevention and fight against fires adapted to the characteristics of the population highlighted in our research.

Limitations

An important limitation of study is the lack of relevant information, so our results could be subject to the “omitted-variable bias” (Mustard 2003). For example, in the case of the Hectares Burned model, we could not obtain data

for developing explanatory variables describing fire-fighting infrastructure, suppression decisions, and response time, among other factors. Furthermore, it would have been interesting to include variables that measured how the prevention and extinction budget was allocated in each municipality. The authors attempted to obtain this information, but never received responses to their request.

The complexity of the subject itself, linking socioeconomic and meteorological variables with forest fires and establishing inter-territorial and inter-temporal differences, is a challenge. The relationships among variables are not always clear or direct, suggesting the use of other techniques such as structural equations.

Finally, to achieve an even deeper analysis, it would be necessary to have information on many more socio-economic or even attitudinal variables, differentiated by even smaller territorial units, such as the parish. Currently, this information is not available.

Appendix 1

Galicia, Spain's most wildfire-prone region

Galicia is a Spanish region located in the northwest of the Iberian Peninsula. It is formed by the provinces of A Coruña, Lugo, Ourense and Pontevedra, which in 2015 encompassed 314 municipalities (313 in 2021) grouped in turn into fifty-three counties. Galicia has 2,695,645 inhabitants (INE 2021). The traditional organization of the population is substantially different from that of the rest of Spain: the territory of each municipality was divided into parishes, which in turn comprised several localities. Galicia is characterized by its high rate of demographic dispersion, which, together with a high number of towns, means that 50% of the population entities in Spain are in Galicia, occupying only 5.8% of the total area (INE, 2021).

Most of the population is grouped in the coastal areas between the cities of Ferrol and A Coruña in the northwest and between Villagarcía d'Arousa, Pontevedra and Vigo in the southwest Figure 3.

Galicia has been the Spanish autonomous community most affected by wildfires since the beginning of the twenty-first century. This can be seen in Fig. 4 that compares Galicia and Spain in terms of hectares burned and number of wildfires. In addition, because of the lengthening of fire season within Europe, Northern Spain and Portugal are the most critical areas.

Fires in Galicia have weighed significantly in Spain's general statistics. As shown in Fig. 5, in certain years, both the number of wildfires occurred and burned hectares in Galicia exceed 50% of Spanish fire disasters. Moreover, although the number of fires has decreased, burned hectares follow a cyclical nature and its mean is constant.



Fig. 3 Location of Galicia

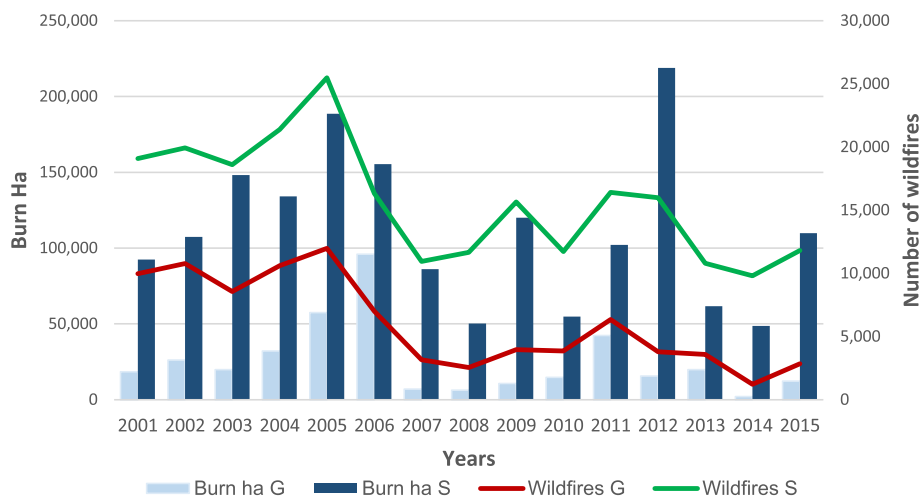


Fig. 4 Relation between Galicia (G) and Spain (S). 2001–2015. Burned hectares (ha) and number of wildfires. Source: De Diego et al. (2019)

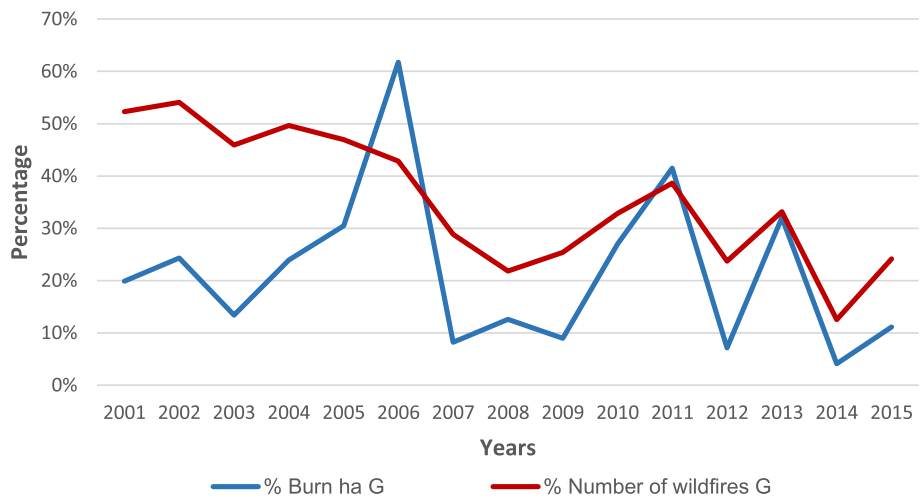


Fig. 5 Burned ha and number of wildfires in Galicia in relation to Spain. 2001–2015. Source: De Diego et al. (2019)

Appendix 2

The methodological process

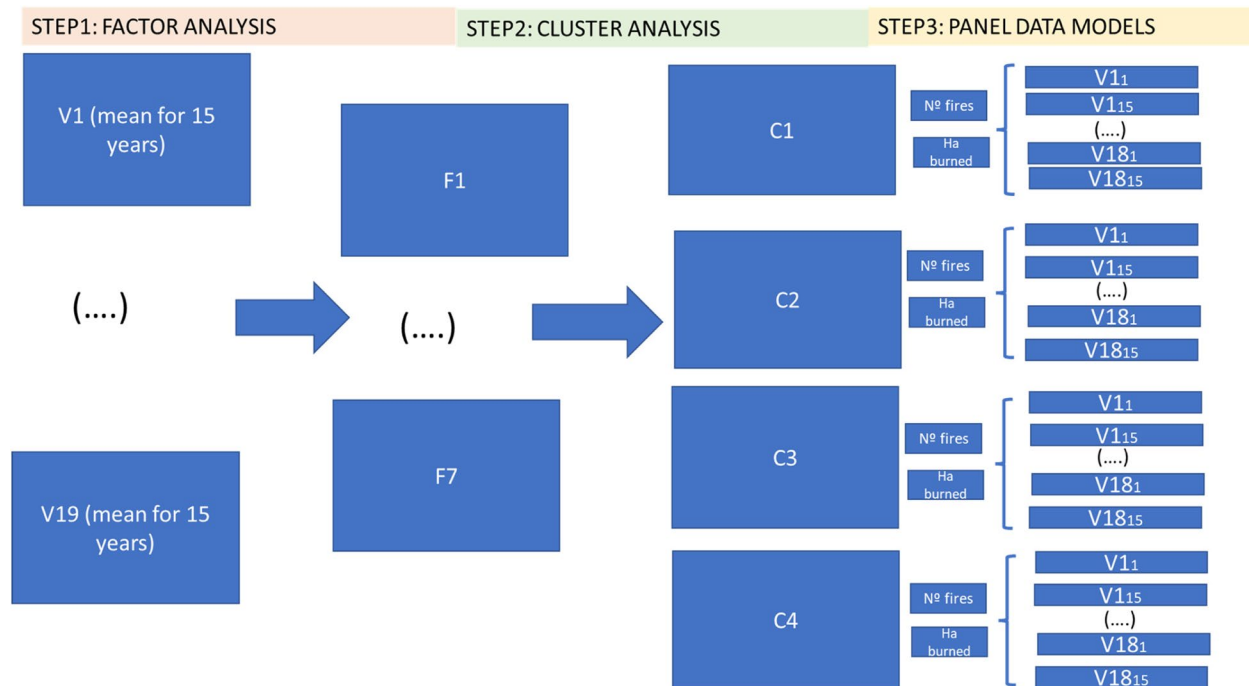


Fig. 6 Outline of the methodological process

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Authors' contributions

Conception: MF, AR, and JdD. Design: AR, MF, and JdD. Data acquisition: JdD. Data analysis: JdD, AR, and MF. Data interpretation: JdD, MF, and AR. Work drafting: JdD, MF, AR, and JK. Revision: MF, AR, JK. The authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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