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Interacting effects of topography, vegetation, human activities and wildland-urban interfaces on wildfire ignition risk

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Abstract

Effective fire prevention requires a better understanding of the patterns and causes of fire ignition. In this study, we focus on the interacting factors known to influence fire ignition risk, such as the type of vegetation, topographical features and the wildland-urban interface (WUI; i.e. where urban development meet or intermingle with wildland). We also analyze the human activities and motivations related to fires and whether they differ depending on the type of vegetation and the location within/outside WUI. There were significant interactions between topography, type of vegetation and location within/outside WUI. The risk of ignition was in general higher at lower elevations, and this tendency was more marked in forested land covers (all plantations and open woodlands), with the noticeable exception of native forests. North-facing sites had lower fire ignition risk outside the WUI, especially in native forests, while southern aspects showed higher fire ignition risk, especially in open shrublands. However, this effect of the aspect was only significant outside WUI areas. In relation to causes, there were also interactions between human activities/motivations related to fires, the type of vegetation and the location within/outside WUI. All forestry plantations appeared clustered in relation to fire causes, especially in the WUI, with high incidence of deliberately caused fires related to violent or mentally ill people and rekindle fires. In contrast, native forests, despite structural similarities with forestry plantations, showed more similarity with agricultural areas and open woodlands in relation to fire causes. In shrublands, there was a relatively high incidence of fires related to ranching, especially outside the WUI. This pattern of interactions depicts a complex scenario in relation to fire ignition risk and prompts to the importance of taking this complexity into account in order to adjust fire management measures for improved effectiveness.

Keywords: wildfire ignition risk, Galicia, forest fires, human-related causes, topography, Spain, WUI

Abbreviations

WUI: Wildland-urban interface
LULC: land use/land cover
Agr: Agriculture areas
OpShr: Open shrublands
Shr: Shrublands
OpWd: Open woodlands
AtlF: Atlantic forests
PiP: Pine plantations
EuP: Eucalypt plantations
MxAtl: Mixed Atlantic forests
MxEuPiP: Mixed plantations of pines and eucalypts
MxPiP: Mixed pine plantations
MxEuP: Mixed eucalypt plantations

1. Introduction

Fire is an important agent of change in natural ecosystems that has driven species adaptations and shaped landscapes over millions of years. As a consequence of human activities, current fire regimes have changed dramatically in many areas compared to natural regimes, causing impacts in both natural ecosystems as well as in the human society (Bowman et al. 2011). For the need to better understand fire patterns and improve fire prevention measures, there is an increasing interest on fire causes and risks. Fires occur as a consequence of both natural and human causes, with weather, topography, type of vegetation or proximity to human settlements being decisive factors in determining the likelihood of fire occurrence (e.g., Moreira et al. 2011).

The type of vegetation, as a land use/land cover (LULC) type, has been shown to be especially relevant for fire ignition risk (e.g., Bajocco and Ricotta 2008; Carmo et al. 2011; Cumming 2001; Nunes et al. 2005). Vegetation types differ in fuel loads and flammability as well as on fuel continuity, as determined by the structure of vegetation (Saura-Mas et al., 2010). For instance, in NW Spain, native forests and agricultural areas have the lowest fire ignition risk, whereas shrublands and mixed forestry plantations have the highest ignition risk (Calviño-Cancela et al. 2016). Knowledge on the fire ignition risk associated to different vegetation types can inform landscape management policy decisions, which can promote vegetation types with lower fire ignition risk.

LULCs have been shown to interact with other factors such as the proximity of human settlements (Calviño-Cancela et al. 2016). In relation to this, wildland-urban interfaces (WUIs) have been defined as areas where urban development meet or intermingle with wildland, and this interfaces are of special concern for fire risk management since fires are usually more frequent in these areas and the danger to human lives and properties can be higher there (e.g., Cohen 2000). The only study, to our knowledge, addressing this interaction between LULC and the WUI revealed that the fire ignition risk associated to different LULC does differ between WUI and non-WUI areas, with forestry plantations showing the highest increase in the likelihood of fire occurrence in WUI compared to non-WUI areas (Calviño-Cancela et al. 2016). Topography can also interact with LULC to modify fire risk, since it affects the distribution of vegetation (e.g., agriculture fields are usually located in flat, low areas, while forest and plantations usually occupy steeper areas, less suitable for agriculture) and some abiotic factors such as temperature and moisture content of fuels (e.g., in North versus South facing slopes).

In addition to these elements, nowadays the human factor is essential to understand the patterns of fire risk. Human activities have altered fire regimes worldwide, modifying fire frequency, intensity, and size of wildfires (Bowman et al. 2011). Human-related causes, whether intentional or by accident, are the most frequent causes of fires (FAO 2007). In addition, certain human uses or activities are specifically associated to particular LULCs, being important drivers of fire risk in those LULCs. Common examples are agricultural burnings in farmlands or the periodical burnings in shrublands and grasslands to control woody encroachment and promote growth of new shoots, grasses and forbs for grazing (Ganteaume et al. 2013; Vélez 2002; Webb 1998). Similarly, socioeconomic factors, such as fragmentation of holdings, that limits the profit owners obtain from forestry products, urbanisation pressure, rural land abandonment or conflicts associated to forests' multiple uses have been shown to increase the probability of fire (e.g., Chas-Amil et al. 2015; Romero-Calcerrada et al. 2010; Yang et al. 2007). Moreover, since population density, human behaviour and activities differ markedly between WUI and non-WUI areas, human-related factors are expected to modify the fire ignition risk associated to LULCs and topographical features depending on their location within or outside WUIs areas. Topography can also affect the risk of fire related to human causes, since human accessibility and activities can be markedly determined by topography (e.g., high and abrupt areas are less accessible).

In this study, we assess the fire ignition risk focusing on the interacting effects of LULC types, the WUI and topographical features. We also analyze the underlying causes related to fire occurrence, focusing on human activities and motivations, and how this is affected by location within or outside the WUI in different LULC types.

2. Materials and methods

2.1. Study area

This study was carried out in Galicia (NW of the Iberian Peninsula; Fig. 1), the most important forestry region in Spain (Manuel and Gil 2002), where c. 70% of the land is forested, mainly covered by tree plantations of *Pinus pinaster* and *Eucalyptus globulus*, in pure and mixed stands. Native forests dominated by *Quercus robur* have higher species diversity and more distinctive communities than tree plantations (Calviño-Cancela et al. 2012a, 2012b, Calviño-Cancela 2013), but are reduced to small, isolated patches (Díaz-Maroto and Vila-Lameiro 2008; Teixido et al., 2010). Eucalyptus plantations have expanded notably in the last decades, both by intentional planting and natural spread (Aguas et al. 2014, Calviño-Cancela and Rubido-Bará 2013, MAGRAMA, 2011). The frequency of wildfires is especially high in the study area: more than 30% of forest fires in Spain each year occur in this region, mainly associated with intentional behavior (75%) (MAGRAMA 2012).

2.2 Data

A database of 26,838 wildfire reports for the period January 1st, 2006 to December 31st, 2011 obtained from the Spanish Forest Fire Statistics (EGIF) was used in this study, which includes the coordinates of each ignition point (see Calviño-Cancela et al. (2016) for details). Fire causes and motivations given in fire reports were grouped in 12 categories focusing, for deliberate and negligent fires, on human activities and behaviours to which the fire ignition was related: agriculture and vegetation management (including agricultural burnings and fires related to verge maintenance), ranching (fires related to pasture regeneration), forestry management, hunting, recreation, waste management (rubbish burning), profit gaining, conflicts, mentally ill or violent people, accidents, natural (lighting) and rekindle (Table 1). Fires caused by “other negligences”, “other deliberate causes” and with “unknown causes” were excluded from the study, due to the lack of definition of these categories, as they may include very different causes.

For each fire ignition point we determined the land use/land cover type (LULC), its topographic features (slope, elevation, and aspect) and the location inside or outside of the WUI. We determined the LULC type using information from the Fourth National Forest Inventory (IFN4, MAGRAMA 2011; see Calviño-Cancela et al. (2016) for further details). Areas with no or very scarce vegetation (e.g., water bodies, beaches, or artificial surfaces such as industrial or urban areas) were excluded, as well as the less frequent LULCs (grasslands, Mediterranean forests and Acacia woods), due to the low number of fires in WUI in these categories. WUI was defined as the area within a 50 m radius around buildings at a distance of up to 400 m from wildland vegetation (Law 3/2007 of April 9, 2007, addressing the issues of wildfire prevention and suppression, as modified by Law 7/2012 of June 28, 2012 of Galician Forestry). The mapping of WUIs in Galicia was obtained from Chas-Amil et al. (2013).

Topographic variables were calculated using the Spatial Analyst extension to ArcGIS® 10.2.2 by ESRI to derive the slope, elevation and aspect, based on a 10 m spatial resolution digital elevation model (DEM, 1:5,000 scale), developed by SITGA (Galician Territorial Information System). The slope was defined as a percentage and elevation in meters. Aspect was defined as the compass direction that the slope faces: N (315º to 360º and 0º to 45º), E (45º to 135º), S (135º to 225º) or W (225º to 315º) direction.

2.3. Data analyses

In order to compare the patterns of distribution of ignition points with a random model, we selected 26,838 random locations in the region and characterized them in regard to WUI, LULCs and topography, as done for ignition points. To select random points we used the module Random Points Generation of Hawth's Analysis Tools, in ArcGIS. Then, we obtained 100 samples with 5,000 locations each, out of the 26,838 fire ignition and random points, using a Montecarlo method (bootstrapping; random resampling with replacement; Efron 1982, Manly 1998).

In relation to topography, we tested whether there were differences in elevation between ignition and random points, WUI/non-WUI areas and LULCs with ANOVA, with Random/Fire, WUI/non-WUI and LULCs as fixed factors and the elevation as the variate. For differences in slope, we followed the same approach but using a generalized linear model with the negative binomial distribution and logratio as the link function, because slope followed a negative binomial distribution instead of a normal distribution. To analyse the effect of the aspect (N, S, E and W, a categorical variable), we calculated the proportional differences between the number of fires recorded in each combination of topographic features x LULCs x within/outside WUI and that in the random set, which corresponds to the expected number according to a random probability. This is equivalent to selection indexes used in other studies (e.g., Moreira et al. 2001; Bajocco and Ricotta 2008), since proportional differences are the observed minus the expected frequencies divided by the expected frequencies. We performed an ANOVA with LULC and within/outside WUI as fixed factors and the proportional differences between the fire and random sets in each compass aspect (N, S, E and W) as variates.

In relation to causes, we used again a Montecarlo method to resample from the original set of ignition points, obtaining 100 samples with 100 cases per each LULC category within and outside the WUI. Shrublands and Open shrublands were pooled together for this analysis. We used PERMANOVA to analyse differences in the causes of fires as affected by LULC and location within/outside the WUI (fixed factors). The proportion of fires for each cause in each combination of LULC and WUI/non-WUI was used as the variate. We used 9999 permutations for the analyses, with type III sums of squares, fixed effects sum set to zero and permutation of residuals under a reduced model. We used NMDS (non-metric multidimensional scaling) ordinations to represent graphically the difference between LULCs within and outside the WUI, showing the distance between LULCs in the fire-causes space. For the sake of clarity in figure 5, we used only 30 randomly chosen samples out of the 100 samples per LULC. To represent the main fire causes driving the patterns of distances (divergences) between LULCs in the NMDS ordinations, we calculated the spearman rank correlation of each fire cause with the axes and represented those with $r > 0.5$. Both PERMANOVA and NMDS ordinations were based on Bray-Curtis similarities of square-root transformed data. We used PRIMER 6.1.12 (Clarke and Gorley 2006) with the PERMANOVA + 1.0.2 add-on (Anderson et al. 2008) for these analyses.

3. Results

3.1. Topography

We found 2nd and 3rd order interactions of Ignition/Random with WUI/non-WUI and LULCs in relation to elevation (Table 2) and slope (Table 3), which means that the divergence in elevation and slope between random and ignition points differed between WUI and non-WUI areas and depending on the LULC. For elevation, ignition points had in general lower elevation than random points (Fig. 2). This pattern was noticeable in tree plantations, with 14-39% lower elevation in ignition points, whereas differences in the rest of LULCs were lower than 10%. In addition to tree plantations, this pattern was also noticeable in mixed Atlantic forest and open woodlands within the WUI (17% and 15% lower, respectively), whereas ignitions in open shrublands had in the WUI higher elevations than expected under the random model (35% higher), in contrast with the similar elevation between random and ignition points outside the WUI (Fig. 2). Regarding slope (Fig. 3), agricultural areas had the lowest slope (c. 10%), that was similar in ignition (10.4%) and random points (10.1%) in non-WUI areas, with higher slopes for ignition points in the WUI (12%). Slopes were similar in the rest of LULCs, varying between 16% and 29% in random points and 16-24% in ignition points. Despite higher slopes outside the WUI in random points (18% on average), fires occurred at similar slopes within and outside the WUI, thus at flatter areas than average outside the WUI but steeper than average within the WUI, except for MxAtl, with ignition points tending to be in flatter areas in the WUI (Fig. 3).

There was a clear contrast between WUI and non-WUI areas in the risk of fire ignition associated with aspect (Table 4; Fig. 4). Outside the WUI, the percentage of fires occurring in sites facing North was lower than expected by random chance, especially in Atlantic forests (AtlF and MxAtl; Fig. 4). In contrast, southern aspects showed the opposite pattern, especially in open shrublands (Fig. 4). Within the WUI, however, there was not a clear pattern in regard to aspect (Fig. 4).

3.2. Fire causes

The PERMANOVA analysis of differences in the causes of fires revealed a significant effect of both locations within/outside the WUI and the LULC, as well as a significant interaction between these two factors (WUI:LULC, Table 5). Despite this interaction, the general pattern was similar outside and within the WUI, as showed in the distribution of LULCs in the causes space (NMDS ordinations; Fig. 5). All plantations appeared clustered in this ordination (EuP, MxEuP, PiP, MxPiP, and MxEuPiP; on the right in Fig. 5), especially outside the WUI, which reveal similarities in the causes associated with the fires occurring in these LULCs. The difference between plantations and other LULCs (shrublands, Atlantic forests, agricultural areas and open woodlands) was mostly due to a higher frequency of fires in plantations caused by violent or mentally ill people and, in a lesser degree, of rekindle fires outside the WUI, as well as a lower incidence of fires related to ranching, and to agriculture and vegetation management outside the WUI (Table 6). Shrublands appear as the most distant to plantations (Fig. 5), with Atlantic forests, agricultural areas and open woodlands occupying intermediate positions. Shrublands differ mainly because of the relatively high incidence of fires related to ranching, especially outside WUIs, and the highest frequency of fires related to hunting, although this activity caused a low number of fires (1.6%). Agricultural areas and open woodlands appear very close in the fire causes space, especially in the WUI, where they intermingle (Fig. 5). The relative importance of the different fire causes is very similar in these LULCs, especially in relation to rekindle fires, fires caused by mentally ill or violent people, and related to agricultural and vegetation management (Table 6). Recreation was mainly related to Mixed Atlantic forests, particularly in the WUI.

4. Discussion

4.1. Topography

As shown in previous studies, topography had a significant effect on the risk of fire (e.g., Carmo et al. 2011, Guglietta et al. 2015, Oliveira et al. 2013) but, interestingly, this effect differed depending on the LULC and the location within or outside WUI areas. These interaction effects have not been previously explored in detail, despite their interest for management. There was a general tendency of higher fire ignition risk at lower elevations. However, this tendency was not consistent for all LULCs within/outside the WUI. It was more marked in forested land covers (all plantations and open woodlands), with the noticeable exception of native forests (AtlF). A higher fire ignition risk at lower elevations has been related to better accessibility (more and better roads at low elevation), which increases the risk of human-related fires both within and outside the WUI (Chas-Amil et al. 2015; Ganteaume et al. 2013). The impact of this increasing accessibility might have been especially important on deliberate fires, and the high incidence of fires caused by arsonists in plantations might explain the notable effect of low elevation in these land covers, in contrast with native forests, where these fires are relatively infrequent. Shrublands and agricultural areas showed also a contrasting pattern, with a striking higher ignition risk at higher elevations observed in open shrublands in the WUI. Shublands had the highest average elevations of all vegetation types considered (c. 780 m outside the WUI and c. 530 m in the WUI in contrast with an average of c. 410 m and 330 m, respectively, in the rest of LULCs), and suffer the highest ignition risk in the region (Calviño-Cancela et al. 2016).

The most common causes of ignition in this vegetation type are related to the use of fire as a tool, for vegetation management and in relation to ranching. Limited accessibility does not probably discourage ranchers and farmers in the same way as arsonists, who need a quick escape. On the other hand, at the high elevations typical of shrublands, the microclimate may play an important role, with higher elevations having dryer and windier conditions, which increase fire hazard. In addition, limited accessibility could increase the risk of spread of these fires, for it complicates fire-fighting operations.

Accessibility can also explain the higher ignition risk of flatter areas outside the WUI, where steeper areas are difficult to access. Within the WUI, fires occurred at similar steepness than outside the WUI but, since the terrain is flatter in general, these areas were steeper than average. The flattest areas within the WUI are occupied by the more valuable uses (e.g., residences or crops), more protected against fire.

In relation to aspect, lower ignition risk in northern slopes is a common pattern in temperate zones in the northern hemisphere (see e.g., González et al. 2005, Mermoz et al. 2005; but see Carmo et al. 2011). North facing slopes receive less solar radiation, which translates into lower temperatures, higher moisture contents and thus reduced flammability. The shade effect is more pronounced at lower sun elevation angles (i.e., at higher latitudes and closer to the winter solstice) and at steeper slopes. This explains the interaction with the WUI: the terrain is flatter within WUIs, which reduces the shade in north facing slopes. The effect of reducing fire ignition risk in northern slopes outside the WUI was more marked in tree covered land covers and, especially, in native forests (AtlF and MxAtl), where the dominant broadleaved trees (e.g. *Quercus robur*, *Castanea sativa*) contribute to maintain the typical fresh and humid microclimate of northern slopes and to reduce fire risk.

4.2. Fire causes

Human activities have been shown as important determinants of fire occurrence in the region. Increased fire ignition risk in WUIs is the result of the proximity of human settlements that affects the kind of activities performed in the surrounding landscape (Bar-Massada et al. 2014). Fire ignitions were most frequently related to agriculture and vegetation management, despite regulations devised to limit fire hazards (e.g., banning of agricultural burnings in summer) (Moreira et al. 2011). More awareness among citizens regarding the danger involved in this activity is thus necessary.

The distribution of LULCs in the causes space, as depicted in the ordination (Fig. 5), was very intuitive, with LULCs that seem *a priori* similar (for instance in terms of habitat structure, species composition or uses) appearing close, for the accompanying similarity in the causes of their fires. This is very revealing of the close relationship between causes and LULCs. For instance, all forestry plantations appeared clustered, especially outside the WUI, and at a certain distance from native forests (AtlF), which are very similar in structure. Note the higher incidence in forestry plantations of deliberately caused fires related to violent or mentally ill people. The economic value of these plantations may make them the target for individuals willing to cause damage to land owners. However, most fires in this category (68.6%) were assigned to pyromaniacs, which are supposed to have no conscious motivation to set fires. But the incidence of fires related to this mental disorder are often overestimated, due to the poor understanding of this condition by fire reporters and officials (Doley 2003 and references therein), which may be hiding the true conscious motivations of arsonists. AtlF appeared relatively close to agriculture (Agr), with open woodlands (OpWd) occupying intermediate positions. AtlF are expanding in some areas as a result of natural regeneration after land abandonment by farmers in rural areas (Calvo-Iglesias et al. 2009, Corbelle-Rico et al. 2012). Thus, their proximity to active agricultural areas may explain their similarity in fire causes. This would also explain the intermediate position of OpWd, which are often transitional stages of colonization of abandoned fields towards forests or mixed formations (Calvo-Iglesias et al. 2009; Escribano-Avila et al. 2014). The relatively high incidence of fires related to ranching in shrublands, especially outside the WUI, is probably related to their use for extensive livestock grazing, since deliberate periodical burnings have been traditionally practiced in these areas to provide a flush of new growth more nutritious for grazers (Webb 1998). Shrublands are also especially important for hunting in Galicia, where hunting is centred on small game and particularly on rabbits (*Oryctolagus cuniculus*), which are most abundant in this type of habitat (Gálvez-Bravo 2011, Tapia et al. 2014).

4.3. Implications for management

Our results highlight the importance of considering the interactions between factors known to influence fire ignition risk, such as the WUI, LULCs and topography. The pattern of interactions found depicts a complex scenario in relation to fire ignition risk and prompts to the importance of taking this complexity into account in order to adjust fire management measures for improved effectiveness. A better understanding of the fire ignition risk associated with different landscape features, such as vegetation, topography and proximity to urban areas, together with the underlying human-causes of fire ignitions increases the efficiency in the allocation of fire prevention measures such as surveillance or vegetation management, and facilitates the devising of regulations or education campaigns focused on increasing citizen awareness on the fire hazards related to particular activities or behaviours in certain environments (e.g. vegetation management practices in agricultural land and native vegetation, and arsonists in forestry plantations). As commented previously, knowledge on the effect of vegetation on the risk of fire is especially interesting for fire prevention since vegetation can be subject to active management. Our results show that other factors such as topography and location within or outside the WUI, and differences in fire causes may affect the fire proneness of vegetation types. Certain vegetation types show more fire resistance in certain contexts (e.g. Atlantic forests in northern slopes in non-WUI areas), so that they can be used, or be promoted, to reduce fire hazard at the landscape scale. On the other hand, land covers that are particularly fire-prone in certain circumstances (e.g. open shrublands in Southern slopes outside the WUI of in higher altitudes in the WUI), require increased efforts in preventing wildfire occurrence.

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Table 1: Fire causes categories used in this study.

Category	Definition
Agriculture and vegetation management	Fires caused by farmers in agricultural burnings, verge maintenance, bush clearing, control of animals considered harmful for crops or livestock and those related to beekeeping.
Ranching	Fires set to promote forage production for grazers.
Forestry management	Fires related to forest works.
Hunting	Fires caused by hunter to facilitate hunting or to protest against hunting restrictions.
Recreation	Fires caused by campfires, fireworks, cigarettes, hot air balloons or children.
Waste management	Rubbish burning.
Profit gaining	Fires set to create job opportunities in fire fighting brigades or restoration activities, to affect wood prices, to force land-use changes or to increase forest productivity.
Conflicts	Fires related to revenges, disagreements related to land ownership, protests against reductions in public investment, expropriations or the establishment of Natural Protected Areas, or caused by political groups to cause social unrest.
Mentally ill or violent people	Fires caused by arsonists, for excitement, in pseudo-religious or satanic rites or by vandals.
Accidents	Fires caused by accidents, related to railroads, electric power, vehicles, engines or machinery or by army manoeuvres.
Natural	Fires caused by lighting.
Rekindle	Restart of fires.

Table 2: Topography. Analysis of differences in elevation between ignition and random points, WUI and non-WUI areas and LULCs using ANOVA.

Source of variation	d.f.	*SS*	*F*	*P* value
Ignition/Random	1	$1.015 \cdot 10^7$	151.83	<0.001
WUI	1	$1.235 \cdot 10^8$	1847.08	<0.001
LULC	10	$1.440 \cdot 10^9$	2154.22	<0.001
Ign/Rand : WUI	1	$2.244 \cdot 10^7$	335.69	<0.001
Ign/Rand : LULC	10	$3.297 \cdot 10^7$	49.32	<0.001
WUI: LULC	10	$4.690 \cdot 10^6$	7.02	<0.001
Ign/Rand : WUI: LULC	10	$1.339 \cdot 10^6$	2.00	<0.001
Residual	50423	$3.370 \cdot 10^9$		
Total	50466	$5.005 \cdot 10^9$		

Table 3: Topography. Analysis of differences in slope between ignition and random points, WUI and Non-WUI areas and LULCs using a Generalized Linear Model with negative binomial distribution and logratio as link function.

Source of variation	d.f.	Deviance (χ^2)	*P* value
Ignition/Random	1	301	<0.001
WUI	1	351	<0.001
LULC	10	7562	<0.001
Ign/Rand : WUI	1	103	<0.001
Ign/Rand : LULC	10	149	<0.001
WUI: LULC	10	211	<0.001
Ign/Rand : WUI: LULC	10	359	<0.001
Residual	50423	41898	
Total	50466	50173	

Table 4: Topography. Analysis of departures between the frequency of ignition points in each compass aspect (N, S, W and E) and that expected by random chance (i.e., obtained in random points) as affected by location within/outside the WUI and LULCs using ANOVA.

Source of variation	d.f.	*SS* (N; S; E; W)	*F* (N; S; E; W)	*P* value (N; S; E; W)
WUI	1	479995; 38934; 518093; 50304	1572.5; 106.6; 1300.8; 122.9	<0.001; <0.001; <0.001; <0.001
LULC	10	9716668; 12741357; 4339542; 2950043	3183.2; 3489.2; 1089.6; 720.9	<0.001; <0.001; <0.001; <0.001
WUI: LULC	10	7267035; 8260603; 386331; 34599694	2380.7; 2262.1; 970.0; 845.5	<0.001; <0.001; <0.001; <0.001
Residual	2178	664828; 795318; 867433; 891248		
Total	2199	18128527; 21836212; 9588383; 7351565		

Table 5: Results of the PERMANOVA analysis on differences in fire causes as affected by location within and outside the WUI and LULC.

Source of variation	d.f.	*SS*	Pseudo*F*	*P* value
WUI	1	58370	771.1	0.001
LULC	9	$3.81\cdot10^5$	559.2	0.001
WUI: LULC	9	$1.50\cdot10^5$	219.4	0.001
Residual	1980	$1.50\cdot10^5$		
Total	1999	$7.39\cdot10^5$		

Table 6: Percentage of fires occurring in each LULC that were associated to different causes, as detailed in Table 1, outside the WUI (upper value) and within the WUI (bottom value).

	Land uses / covers									
Causes	Agr	Shr	OpWd	AtlF	MxAtl	PiP	EuP	MxPiP	MxEuP	MxEuPiP
Agr. & Veg. Management	63.25 55.83	59.16 64.56	57.03 54.37	63.76 61.43	54.74 27.78	36.01 44.44	35.52 47.76	39.80 53.33	36.28 60.00	37.94 50.00
Ranching	7.73 6.95	17.67 10.13	6.40 3.88	9.80 10.00	2.63 11.11	2.31 0.00	3.00 1.49	0.76 0.00	3.98 0.00	2.41 0.00
Forestry Management	0.93 1.64	0.30 0.00	0.61 0.00	0.62 1.43	0.53 0.00	2.31 0.85	3.00 2.99	1.76 2.22	2.65 4.00	1.74 0.00
Hunting	0.96 1.02	5.75 5.06	3.14 1.94	2.40 0.00	2.63 0.00	0.74 0.00	1.43 0.00	1.01 8.89	1.77 0.00	1.07 0.00
Recreation	1.54 3.48	0.48 0.00	1.05 4.85	1.42 0.00	2.11 11.11	2.03 1.71	3.99 7.46	2.02 4.44	2.65 0.00	1.61 2.00
Waste Management	0.80 0.61	0.30 1.27	0.77 0.00	0.53 0.00	1.58 0.00	0.65 0.00	1.14 1.49	0.25 2.22	2.21 0.00	0.67 0.00
Profit gaining	1.03 0.51	0.14 0.00	0.72 0.00	0.18 0.00	0.00 0.00	1.94 1.71	1.00 0.00	1.51 0.00	2.21 4.00	1.47 1.00
Conflicts	1.31 1.43	1.43 2.53	2.10 0.00	2.58 0.00	2.11 5.56	3.32 1.71	3.85 1.49	3.78 2.22	3.10 0.00	2.01 3.00
Mentally ill or violent people	12.06 17.59	5.91 12.66	15.28 17.48	6.06 7.14	17.37 16.67	31.02 33.33	32.67 31.34	30.23 15.56	26.99 24.00	36.73 29.00
Accidents	2.31 4.09	1.23 3.80	2.98 8.74	2.85 10.00	3.68 16.67	3.14 4.27	2.57 1.49	3.02 2.22	4.42 4.00	1.88 2.00
Natural	1.48 1.64	2.73 0.00	3.14 2.91	2.94 4.29	4.74 0.00	6.28 1.71	1.28 0.00	2.77 0.00	1.77 0.00	1.34 1.00
Rekindle	6.61 5.21	4.91 0.00	6.78 5.83	6.86 5.71	7.89 11.11	10.25 10.26	10.56 4.48	13.10 8.89	11.95 4.00	11.13 12.00

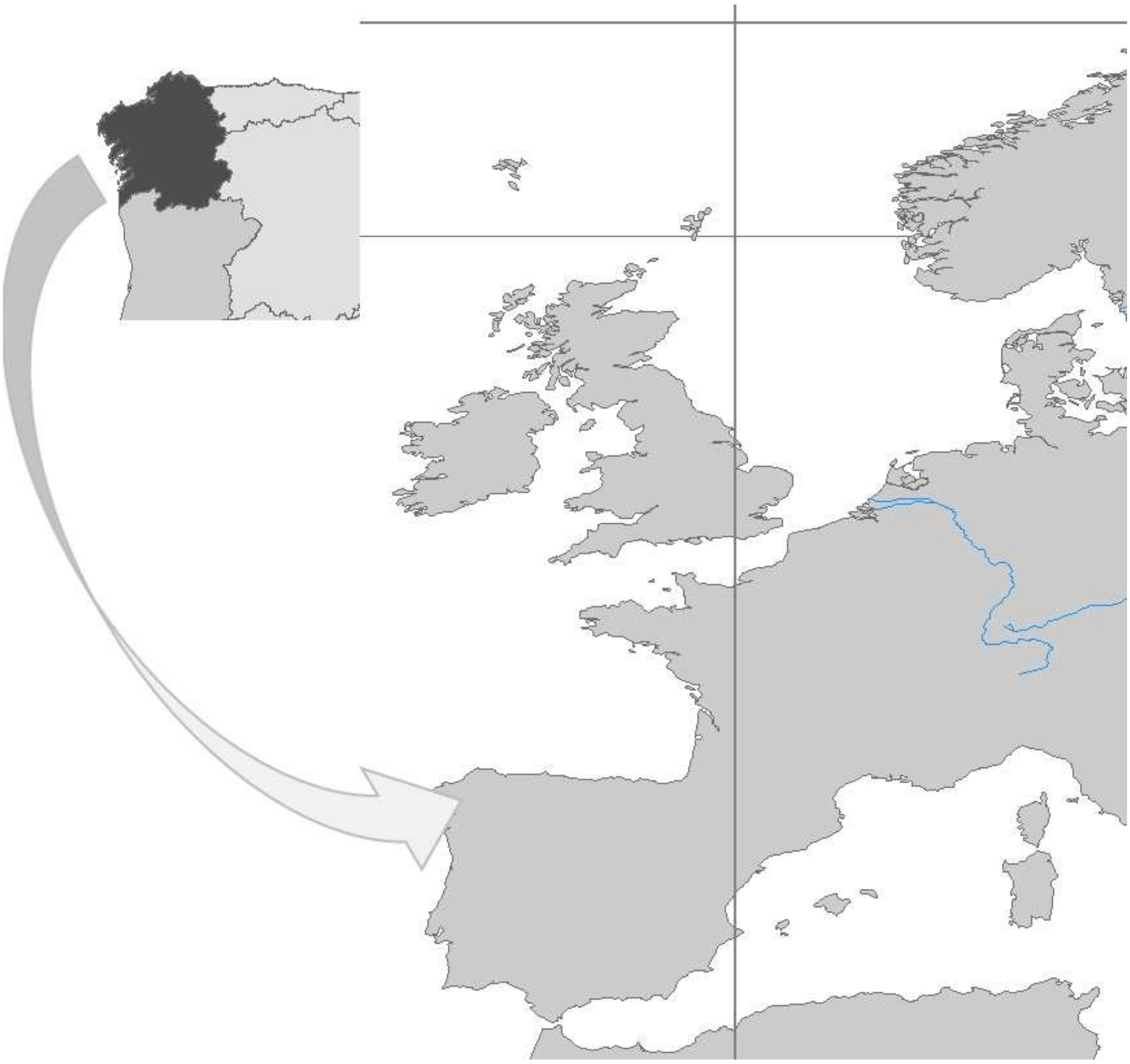

Figure 1: Study area location map.

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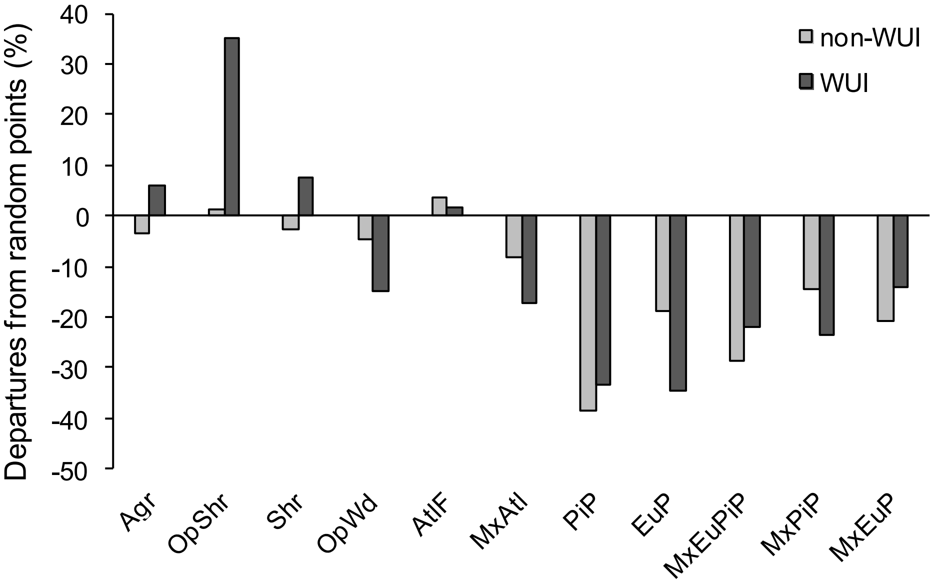

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527 Fig. 2: Differences in elevation (in percentage) between ignition and random points in
528 the LULC types, outside the WUI (light grey) and within the WUI (dark grey).

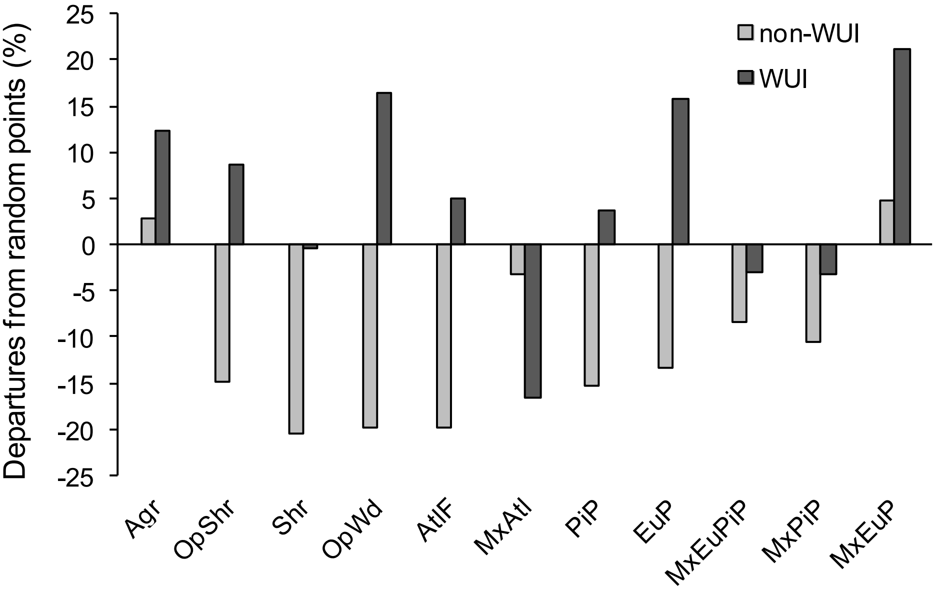

Fig. 3: Differences in slope (in percentage) between ignition and random points in the LULC types, outside the WUI (light grey) and within the WUI (dark grey).

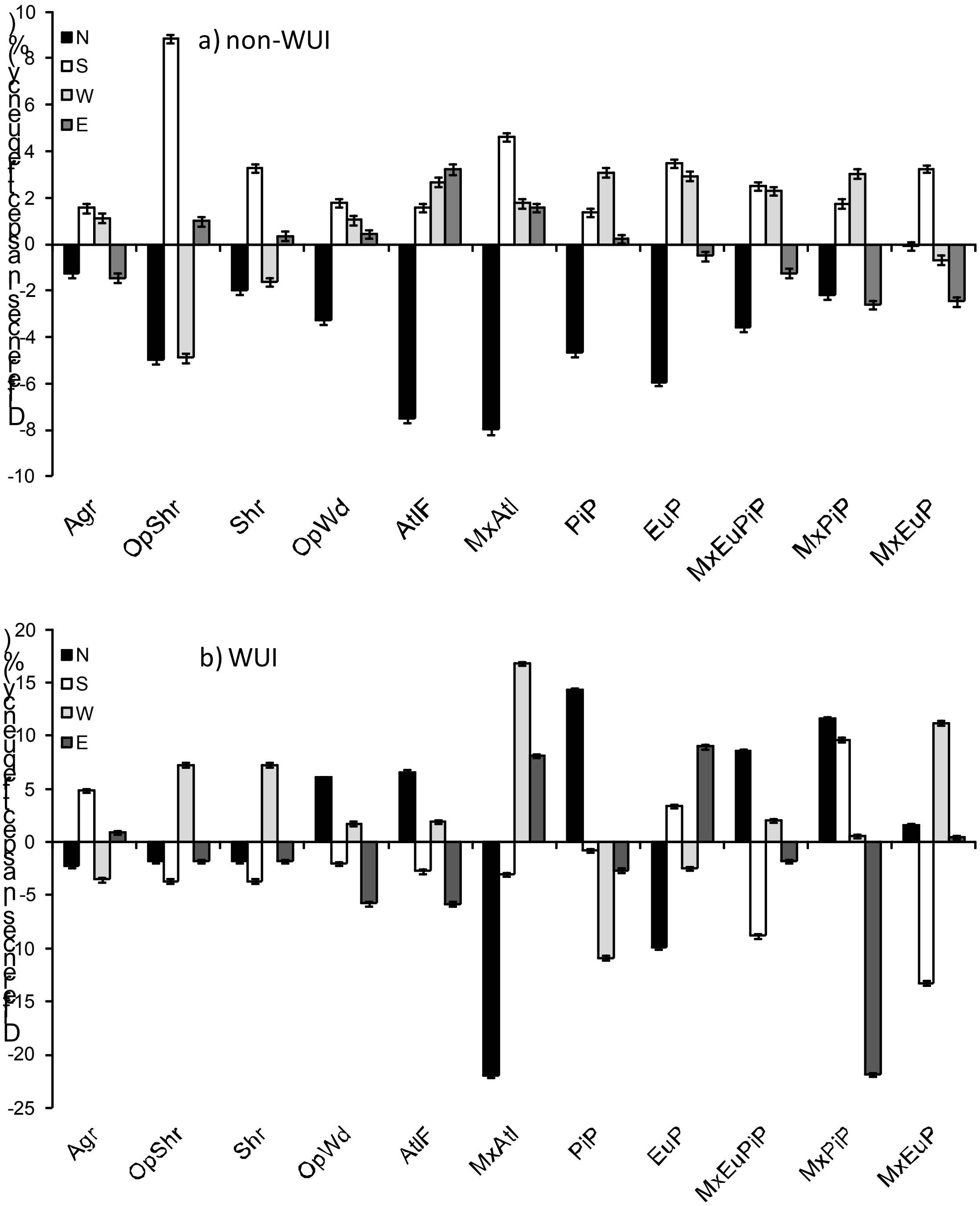

Fig. 4: Fire risk depending on site aspect in non-WUI (a) and WUI areas (b). Departures from 0 show percentage increases or decreases in fire risk compared to that expected by random in each aspect (N, S, W, E) for each LULCs.

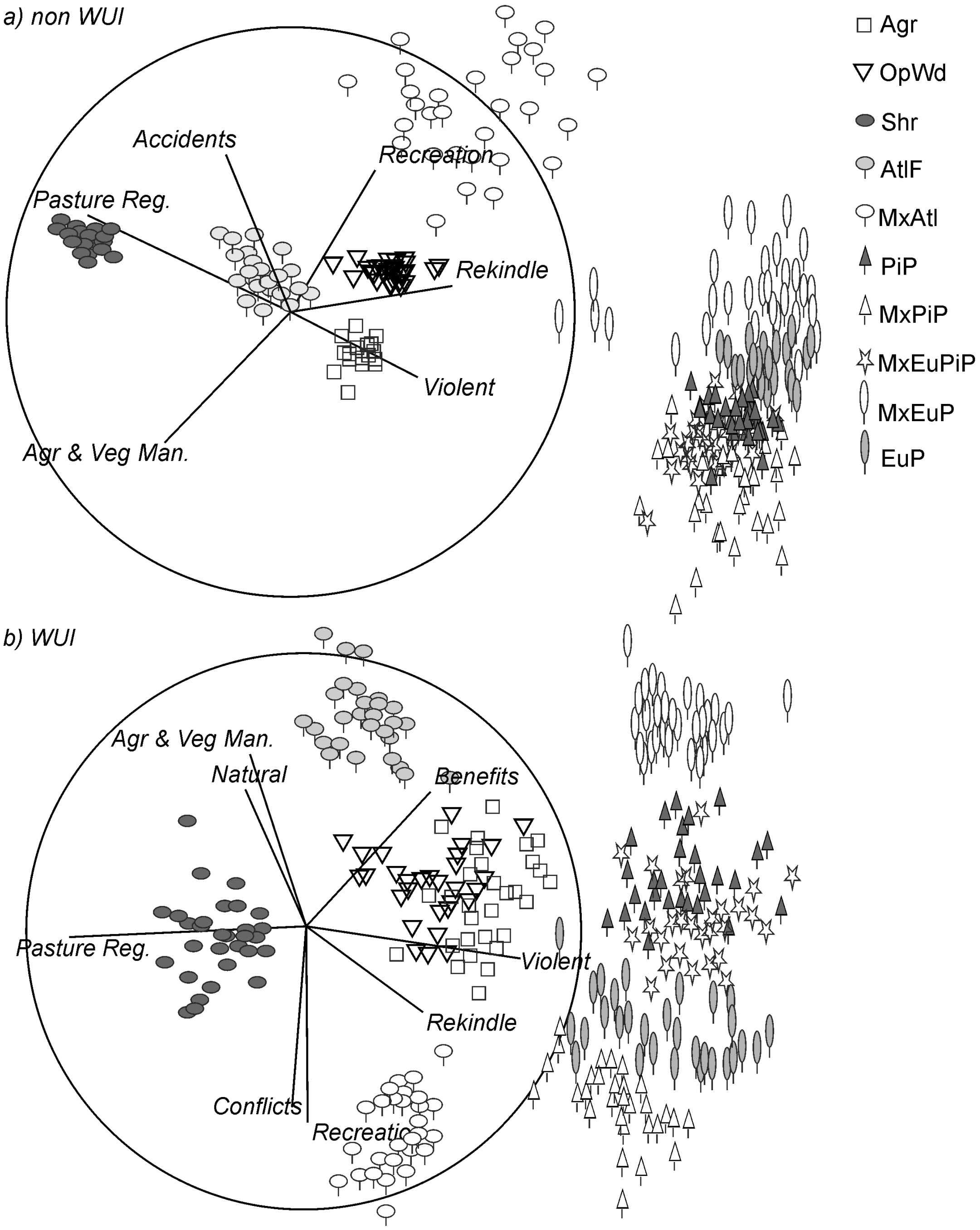

Fig. 5: Fire causes in LULCs. NMDs ordinations of LULC types based on Bray-Curtis similarities on square root transformed data of fire causes in Non-WUI (a) and WUI areas (b), showing distances between LULCs in the fire causes space. See the key for symbols of each type of LULC. Superimposed vectors show the fire causes driving the patterns of distance between LULCs.