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Wildfire risk associated with different vegetation types within and outside wildland-urban interfaces

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Abstract

Wildland-urban interfaces (WUIs) are areas where urban settlements and wildland vegetation intermingle, making the interaction between human activities and wildlife especially intense. Their relevance is increasing worldwide as they are expanding and are associated with fire risk. The WUI may affect the fire risk associated with the type of vegetation (land cover/land use; LULC), a well-known risk factor, due to differences in the type and intensity of human activities in different LULCs within and outside WUIs. No previous studies analyze this interaction between the effects of the WUI and the LULC, despite its importance for understanding the patterns of fire risk, an essential prerequisite to undertake management decisions that can influence fire regimes.

The aim of this study is to assess the effect of the WUI on fire ignition risk and the area burned, and the interaction between its effect and that of the LULC. We used a database of 26,838 wildfires recorded in 2006-2011 in NW Spain and compared fire patterns in relation to WUI and LULC with a random model, using a Montecarlo approach.

There was a clear effect of the WUI on the risk of both fire ignition and spread (higher ignition risk but lower risk of spread in WUIs). The risk of fire was also affected by LULC and, interestingly, the pattern among LULCs differed between WUI and non-WUI areas. This interaction WUI x LULC was particularly important for forestry plantations, which showed the highest increase in ignition risk in WUI compared to non-WUI areas. Native forests and agricultural areas had the lowest ignition risk. Agricultural areas showed the smallest difference in fire size between WUI and non-WUI areas, while shrublands showed much larger fires outside WUIs. Deliberate fires were larger in general than those with other causes, especially outside the WUI.

The differences found between LULCs in fire risk, both in WUI and non-WUI areas, have interesting implications for fire management. Promotion of land covers with low fire risk should be considered as a low cost alternative to the usual fire prevention measures based on fuel load reduction, which require the continuous clearing of vegetation. In this regard, the low fire risk in native forests should be taken into account. Native forests naturally colonize many areas in the study region and require low or no management, in contrast with agricultural areas, also with low fire risk but requiring continuous management in order to avoid colonization by natural vegetation.

Keywords: wildfire risk, forest fires, human-related causes, land uses, Spain, WUI

Abbreviations

WUI: Wildland-urban interface

LULC: land cover/land use

Agr: Agriculture areas

Gra: Grasslands

OpShr: Open shrublands

Shr: Shrublands

OpWd: Open woodlands

AtlF: Atlantic forests

MedF: Mediterranean forests

PiP: Pine plantations

EuP: Eucalypt plantations

Aca: Acacia woods

MxAtl: Mixed Atlantic forests

MxEuPiP: Mixed plantations of pines and eucalypts

MxPiP: Mixed pine plantations

MxEuP: Mixed eucalypt plantations

1. Introduction

Fire represents a major disturbance in forest systems that is estimated to affect an average of 20 million hectares of forests per year, which represents c. 1% of global forest area (FAO 2010, for the period 2003-2007). Wildland-urban interfaces (WUIs) are areas where urban development meet or intermingle with wildland, which means that the interaction between human activities and wildlife is especially intense in these areas. WUIs are of particular concern for fire risk management. Fire risk refers to the chances of a fire starting (ignition risk) and to the probability of fire spreading across the landscape (Hardy 2005; Jappiot et al 2009). Due to the importance of human-related causes of fire, the higher human density and activity in WUIs may translate into a higher risk of fire ignition (e.g., Cardille and Ventura 2001; Syphard et al 2007; Lampin-Maillet et al 2011; Herrero et al 2012; Chas-Amil et al 2013), higher damages to properties, and higher risk to human lives. WUIs have been expanding in the last decades (Theobald and Romme 2007; Montiel and Herrero 2010), both due to rural land abandonment and residential development in wildland (i.e., due to natural vegetation colonizing humanized areas and vice versa), which increases the relevance of these areas for wildfire management.

When and where wildfires would occur is the result of complex interactions among natural and human ignition sources, weather, topography and land cover (e.g., Mermoz et al 2005; Moreira et al 2011). Worldwide, landscapes are increasingly humanized with land cover changes being pervasive (e.g. the conversion of forests to croplands and tree plantations in developing areas or the expansion of forested land in areas of rural abandonment; Lambin et al 2001; Foley et al 2005). Land use/land cover (LULC) has been shown to have a key role on fire risk (e.g., Cumming 2001; Nunes et al 2005; Bajocco and Ricotta 2008; Carmo et al 2011), as it determines fuel load and characteristics such as moisture content or horizontal and vertical fuel continuity (Saura-Mas et al 2010). For example, in Mediterranean areas, shrublands, grasslands and coniferous forest were found to be more prone to fire than croplands and broadleaf forests (e.g., Oliveira et al 2013; Pereira et al 2014; Rego and Silva 2014). Understanding this selectivity of fire towards specific land cover types has been recognized as an essential background for policy making, since LULC, in contrast to other factors such as topography or weather, can be subject to active management. Moreover, as human-related causes (deliberate, negligent or accidental) are the most frequent causes of fires (FAO 2007), cultural, and socio-economic drivers can have a significant effect on the fire risk associated with certain LULCs (e.g., Cardille and Ventura 2001; Sebastián-López et al 2008; Martínez et al 2009; Marques et al 2011; Padilla and Vega-García 2011; Chas-Amil et al 2015). Since population density, human behaviour and activities differ markedly between WUI and non-WUI areas, human-related factors are expected to modify the risk of fire associated to LULCs depending on their location within or outside WUIs areas.

In this study, the effects of the WUI and the land cover on the risk of fire (ignition and area burned) are assessed and the interaction between these two factors analysed. A better understanding of fire risks and related factors is essential to undertake management decisions that can influence future fire regimes.

2. Materials and methods

2.1. Study area

The South of Europe (Portugal, Spain, France, Italy and Greece) is seriously affected by wildfires every year. For example, in the period 2006-2011, these five countries registered more than 280,000 wildfires, burning roughly 2,000,000 ha. Approximately 30% of these wildfires correspond to Spain (European Commission 2014). In Galicia (NW of Iberian Peninsula), where this study was carried out, the annual average in the same period was of more than 4,500 wildland fires and 30,000 ha burned. Galicia is the region of Spain with the highest frequency of fires; more than 40% of wildfires in Spain were located in this region in the decade 2001-2010, even though it represents only 6% of the Spanish territory

(MAGRAMA 2012). In addition, most fires are human-caused (99%), and most are deliberated (75%) (Chas-Amil et al 2010).

Galicia is characterized by a hilly landscape, averaging 530 m.a.s.l. and with highest elevations reaching 2000 m.a.s.l. The climate is Mediterranean in the South East (most interior part) and Oceanic in the rest of the territory. Average annual rainfall varies from c. 800 mm to c. 2500 mm. July is the hottest month with an average temperature of 18ºC and January the coldest with 7ºC.

It is the most important forestry region in Spain (Manuel and Gil 2002), with c. 70% of the land being forested. Depopulation and farming abandonment has led to an increase of forested land, as in many other rural areas in Europe, with the expansion of eucalypt plantations in particularly, resulting in important changes in the regional landscape, mainly in rural lowland areas (Marey-Pérez et al 2006; Cramer and Hobbs 2007). Thus, more than half of the forested area is covered by plantations of *Pinus pinaster* and *Eucalyptus globulus*, in pure and mixed stands. Native forests dominated by *Quercus robur*, which occupied large areas in the past, have been intensively exploited ever since Roman times (Díaz-Maroto and Vila-Lameiro 2008), being now reduced to small, isolated patches (Ramil-Rego et al 1998; Teixido et al 2010).

Based on Chas-Amil et al (2013), the WUI totals 2,442 km^2 in Galicia, which represents 8.3%, with a higher concentration along the Atlantic coast and in the southwest, where dense and very dense clustered building structures predominate. The WUI is characterized by a lower proportion of forested land compared to non-WUI areas (c. 20% vs. 75%), and has a higher level of forest fragmentation. With an area of 29,574.4 km^2 and a population of 2,747,559 people (2014; population density = 92.9 people per km^2), Galicia is characterized by a very disperse population, even though nearly half of the population live in highly populated areas (3,317 people per km^2; IGE 2011). This high population dispersion together with the exceptionally high incidence of fire makes the study of fire risks associated with the WUI especially relevant in this region.

2.2 Data

2.2.1. Fire data

This study used a database of 26,838 wildfire reports obtained from the Rural Affairs Department of the Regional Government (Xunta de Galicia), and the Spanish Ministry of Agriculture, Food and Environment (MAGRAMA) from the period January 1, 2006 to December 31, 2011. Forest fire reports list general information including location, date, burned areas and causes and motivations (Table 1). Only fires affecting wildland vegetation are included in this database. We evaluated the coordinates of fire ignition points by checking the agreement between those coordinates and the district and municipality given in fire reports, using topographic maps (National Topographic Map Series, IGN, scale 1:25,000), and the burned areas as visually identified in Landsat 5 TM images taken in different dates. When inconsistencies between these information sources were detected the point was discarded in most cases, or corrected when possible. All computations were performed with ArcGIS® 10.2.2 by ESRI and Geomedia Professional 6.0 by Intergraph.

Table 1: Fire causes as included in Spanish forest fire reports.

Category	Definition
Natural	Fires caused by lighting.
Negligences	Fires unintentionally caused by human using fire or glowing objects.
Accidents	Fires unintentionally caused by humans without use of fire, related to railroads, electric power, vehicles, engines, or machinery or by army manoeuvres.
Deliberate	Fires intentionally caused both by

	responsible (arsonists) or irresponsible people (mentally ill and children).
Rekindle	Restart of fires.
Unknown	Fires with unknown causes.

2.2.2. Wildland-urban interface

According to the current fire-protection legislation in the region, the WUI was defined as the area within a 50 m radius around buildings at a distance of up to 400 m from wildland vegetation, where bush clearing is compulsory (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 identification and mapping of WUIs in Galicia was obtained from Chas-Amil et al (2013).

2.2.3. Land cover

For each fire ignition point we determined the land use/land cover type (LULC) using information from the Fourth National Forest Inventory (IFN4, MAGRAMA 2011a), which is based on the cartography of the Forest Map of Spain at 1:25,000 (MFE25, MAGRAMA 2011b). IFN4 defines the land use or vegetation in homogeneous polygons of 0.5 to 2 ha in size (depending on cover type), according to a hierarchical classification of 63 land use types and more than 200 types of vegetation communities. We modified this classification according to our research interests, regrouping IFN4 classes into a total of 14 classes (Table 2), using information from the IFN4 on the cover of trees, shrubs and herbs (grasses and forbs) and the identity of the three dominant tree species and their relative dominance. Areas with no or very scarce vegetation were excluded from the analyses (e.g., water bodies, beaches, or artificial surfaces such as industrial or urban areas). The less frequent LULCs (i.e., grasslands, Mediterranean forests and Acacia woods) were used only when WUI and non-WUI areas were pooled, but were removed from analyses in which we distinguished between WUI and non-WUI areas, due to the low number of fires in WUI in these categories.

Table 2. Description of the land cover categories used in this study, and the percentage of area they occupy within and outside the WUI.

Land cover	Abbreviation	Description	Non-WUI (%)	WUI (%)
Agriculture areas	Agr	Land devoted to agriculture, including crop production and pastures (classified as agriculture in IFN4 structural types; codes 71 to 75).	25.8	73.9
Grasslands	Gra	Natural vegetation dominated by grasses and forbs (classified as herbaceous vegetation in IFN4 structural types; codes 31 to 33).	0.2	0.1
Open shrublands	OpShr	Plant communities with 11-60% of shrub cover and no tree cover.	2.8	0.5
Shrublands	Shr	Plant communities dominated by shrubs corresponding to areas with ≥ 60% of shrub cover and no tree cover.	18.3	2.2

Open woodlands	OpWd	Vegetation with tree cover up to 59%.	15.0	5.6
Forests or tree plantations: with ≥60% tree cover				
Atlantic forests	AtlF	Native broadleaved forests typical of the Eurosiberian region, with ≥70% dominance of *Quercus robur*, *Q. pyrenaica*, *Castanea sativa*, *Alnus glutinosa*, *Betula* spp., *Salix* spp., *Acer* spp., *Fraxinus* spp. or *Populus* spp.	10.8	4.0
Mediterranean forests	MedF	With ≥50% dominance of *Q. ilex* or *Q. suber*.	0.1	0
Pine plantations	PiP	With ≥70% dominance of *Pinus pinaster*, *P. sylvestris*, *P. radiata* or, rarely, other conifers.	9.1	3.4
Eucalypt plantations	EuP	With ≥70% dominance of *Eucalyptus globulus*, or, more rarely, *E. nitens* or other eucalypts.	6.6	3.0

Acacia woods	Aca	With ≥50% dominance of *Acacia dealbata*, mostly, *A. melanoxylon* or other acacias).	0.1	0.1
Mixed Atlantic forests	MxAtl	With 50-69% dominance of species typical of Atlantic forests, as listed previously.	2.1	1.4
Mixed plantations of pines and eucalypts	MxEuPiP	Pines and eucalypts are co-dominant, with none of them occupying more than 70% or having ≤ twice the % dominance of the other.	4.4	3.3
Mixed pine plantations	MxPiP	With 50-69% dominance of pines or other conifers, when eucalypts are not present or they occupy less than half of pine occupancy.	2.6	1.9
Mixed eucalypt plantations	MxEuP	With 50-69% dominance of eucalypts, when pines are not present or they occupy less than half of eucalypt occupancy.	1.9	0.8

2.3. Data analyses

We selected 26,838 random locations in the region (the same number as fires recorded) to analyze patterns of fire risk related to WUI and LULCs, using the module Random Points

Generation of Hawth's Analysis Tools, in ArcGIS. Random points were characterized in regard to WUI and LULCs (using the same criteria as for ignition points) in order to compare the patterns of fire distribution with a random model. We used a Montecarlo method (bootstrapping; random resampling with replacement), to obtain a total of 100 samples of 5,000 points out of the 26,838 fire ignition and random points, respectively. We then calculated the proportional differences between the number of fires observed in each combination of LULCs x within/outside WUI and that in the random set, i.e., the expected number according to a random probability. Proportional differences were thus the observed minus the expected frequencies divided by the expected frequencies (this is analogous to selection indexes used in other studies; e.g., Moreira et al 2001; Bajocco and Ricotta 2008). We performed an ANOVA with LULC and within/outside WUI as fixed factors and the proportional differences between fire and random sets as the variate in order to analyse the patterns of fire ignition risk . Data on the size of wildfires had a negative binomial distribution, therefore, to analyse the effects of fire causes, the location of ignition points within/outside the WUI and the LULC on the size of burned areas we used a Generalized Linear Model with negative binomial distribution and logratio as link function. We previously estimated the aggregation parameter of the negative binomial distribution (k) using the RNEGBINOMIAL procedure of GenStat 7th ed.

3. Results

3.1. The risk of ignition

The risk of fire ignition in a particular location was significantly affected by the LULC type and the location within or outside the WUI ($P < 0.001$; Table 3), with a significant interaction between these two factors ($P < 0.001$; Table 3). This means that the pattern of ignition risk among LULCs differed between WUI and non-WUI areas (Fig. 1). The general trend was of higher ignition risk within the WUI for all LULCs except for Agr, with the opposite pattern. Pooling all LULCs, WUI registered 48% more fires than expected by random chance, in contrast with a 4% less than random chance in non-WUI areas. But this increased risk varied widely in magnitude among LULCs, with PiP having the larger increment in WUI compared to non-WUI (>100%) followed by EuP (58%), mixed plantations with eucalypts (MxEuPiP, MxEuP; 52%), and OpWd (51%). Differences were smaller for AtlF, MxPiP and OpShr (36-30%), and for Shr and MxAtl (23-16%). PiP, EuP, MxEuP and OpWd had more fires than expected by random chance in WUI but slightly less outside the WUI, whereas AtlF had less fires than expected by random chance outside the WUI (being the less fire prone LULC), but slightly more than random within the WUI. Mixed plantations with pines (MxPiP and MxEuPiP) and shrublands (Shr and OpShr) had more fires than expected by random both within and outside the WUI. When pooling WUI and non-WUI areas, Acacia woods had the highest fire risk (c. 100% more fires than expected), followed by Shrublands (both OpShr and Shr) and Mixed pine plantations with eucalypts or other trees (MxEuPiP and MxPiP), that had also more fires than expected by random (> 20% more). Native forests (both MedF and AtlF) had the lowest ignition risk (16-25% less fires than expected).

Table 3: Results of the ANOVA on the effects of location within/outside the WUI and the LULC on the risk of fire ignition.

Source of variation	d.f.	*SS*	*F*	*P* value
WUI	1	122.3930	514.97	<0.001
LULC	10	172.7144	72.67	<0.001
WUI : LULC	10	50.8555	21.40	<0.001
Residual	2178	517.6422		
Total	2199	863.6050		

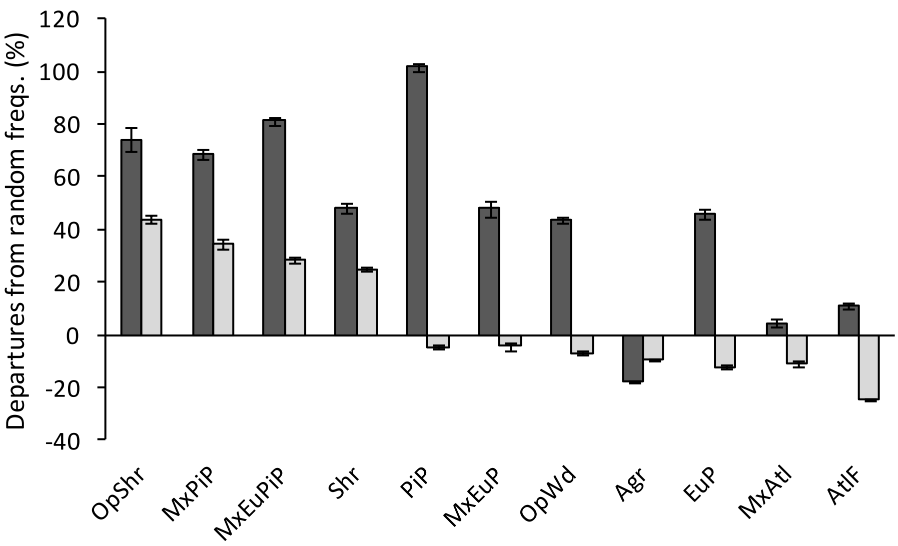


Fig. 1: Percent differences between the number of fires recorded and those expected according to a random distribution among the available LULCs types, in WUI (dark grey) and non-WUI (light grey) areas. LULCs are arranged in descending order in terms of fire risk with WUI and non-WUI areas pooled.

3.2. The risk of fire spread

The area burned per fire was very variable, from less than 0.01 ha up to 7,352 ha, with an average size of 6.7 ha. Data overdispersion (variances larger than means) was apparent in regard to fire sizes (Fig. 2 and 3), with means being larger than medians, 75th or even 90th percentiles in many cases, due to the strong influence that very large fires had on means. Fire causes, location of the ignition point within or outside the WUI as well as LULCs had all a significant effect on the size of fires ($P < 0.001$ in all cases; Table 4). There were also 2nd and 3rd level interactions between fire causes, location within or outside the WUI, and LULC ($P < 0.03$ in all cases; Table 4), which indicates that the pattern of fire sizes among LULCs or causes varied depending on location within or outside the WUI, although this difference was less intense than for ignition risk (see above). In general, fires were smaller within the WUI than outside (mean was 2.7 ± 0.5 in WUI vs. 7.2 ± 0.5 outside WUI, when pooling all LULCs, and medians were 0.1 vs. 0.3, respectively). In Atlantic forests there was one single fire of 710 ha that had a great influence in the mean, making it larger (6.2 vs. 4.0), but fires were in general smaller within the WUI (median size was 0.08 and 0.3 within and outside the WUI, respectively. When pooling WUI and non-WUI areas, fires starting in shrublands were larger than in other LULCs (OpShr and Shr; burned areas averaged 12.9 and 10.3 ha, respectively), and those starting in tree plantations (mean fire sizes varied between 8.8 ha in MxEuP and 5.0 ha in MxPiP) were larger on average than those in agricultural areas (4.9 ha on average) and Atlantic forests (4.2 and 2.9 ha in AtlF and MxAtl, respectively), which had the smallest average sizes.

For fire causes, the pattern of larger fires outside the WUI was consistent for all causes (Fig. 3). Deliberate fires tended to be larger than those with other causes both within and outside the WUI (Fig. 3; higher median and 75^{th} and 90^{th} percentiles), although rekindled fires had a larger mean (despite lower percentiles), for the great influence of a few extreme values on the mean. Non-deliberate fires (caused by accidents, negligences, natural or unknown factors and rekindled fires) had similar size distributions, being usually smaller than 1 ha (Fig. 3). Shrublands had the highest percentage of deliberate fires of all LULCs, with 87 and 89% for Shr and OpShr in WUI and 83 and 85% in those LULCs in non-WUI areas (Fig. 4), compared to 67-78% in WUI and 68-75% in non-WUI in the rest of LULCs (agricultural areas, forest and tree plantations).

Table 4: Results of the analysis on the effects of fire causes, the location of ignition points within/outside the WUI and the LULC on the size of wildfires using a Generalized Linear Model.

Factor	d.f.	Deviance (χ^2)	*P* value
Cause	5	96	<0.001

WUI	1	133	<0.001
LULC	10	459	<0.001
WUI:LULC	10	50	<0.001
Cause:LULC	50	71	0.027
Cause:WUI:LULC	105	134	0.0296

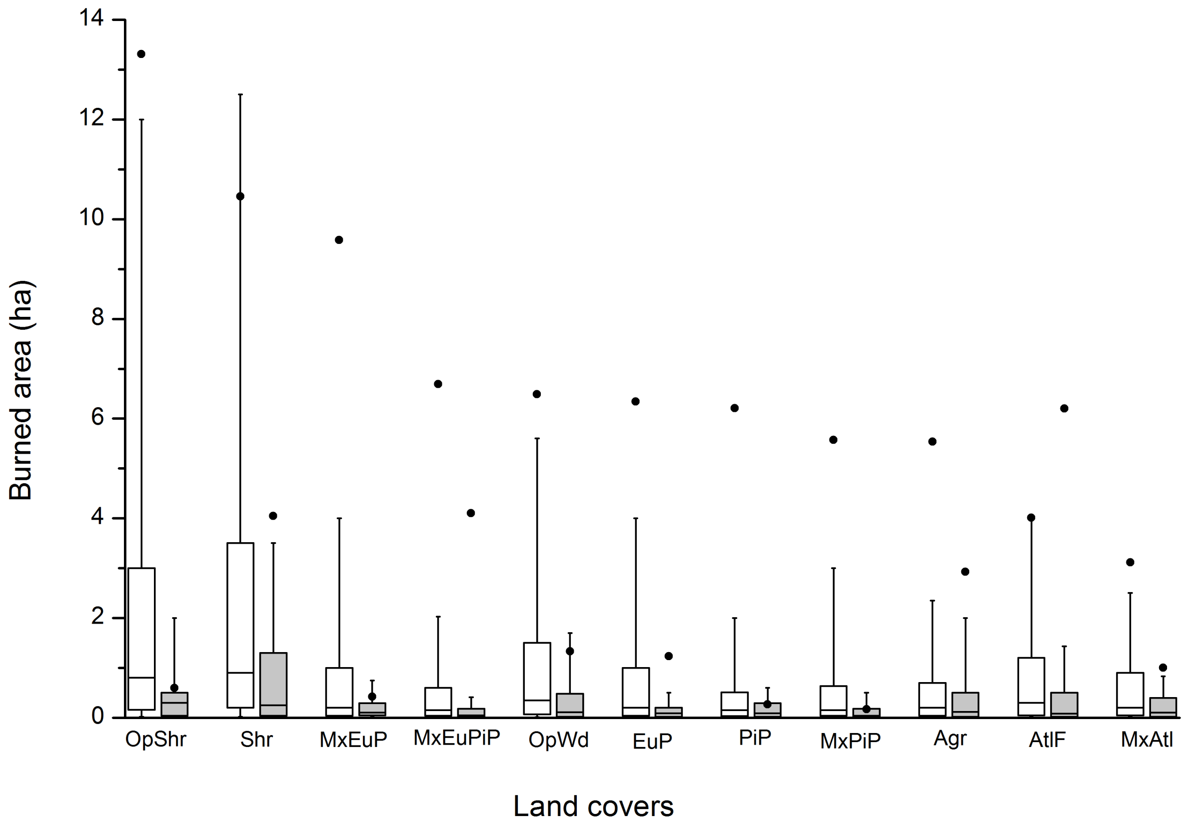


Fig. 2: Total area burned in fires ignited in different LULCs in non WUI (white boxes) and WUI (grey boxes) areas. Means are represented with filled circles; boxes extend from the 25th and 75th percentiles, with medians in the inner horizontal line, and whiskers show the 10th and 90th percentiles. Land covers are arranged according to mean fires sizes for pooled data (WUI and non WUI), in descending order.

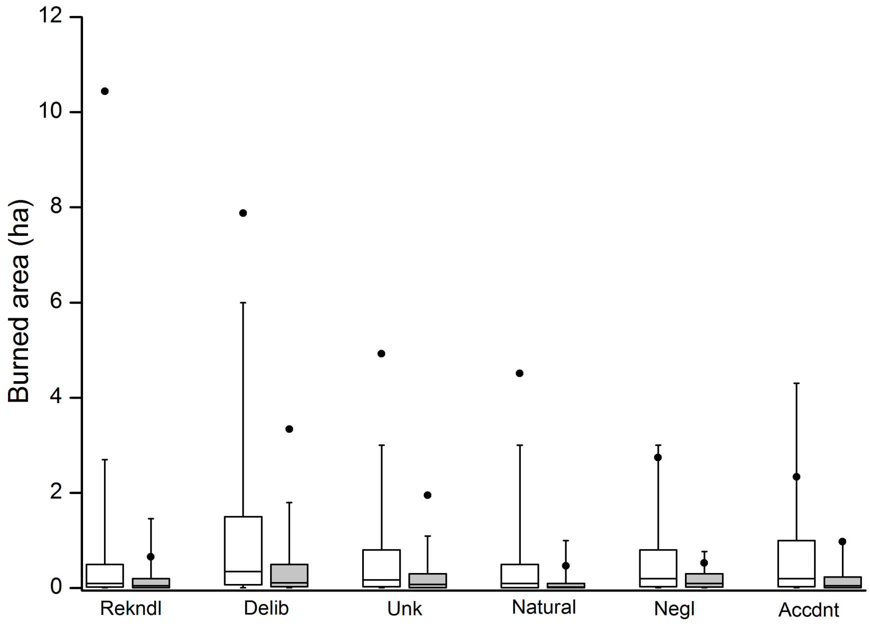
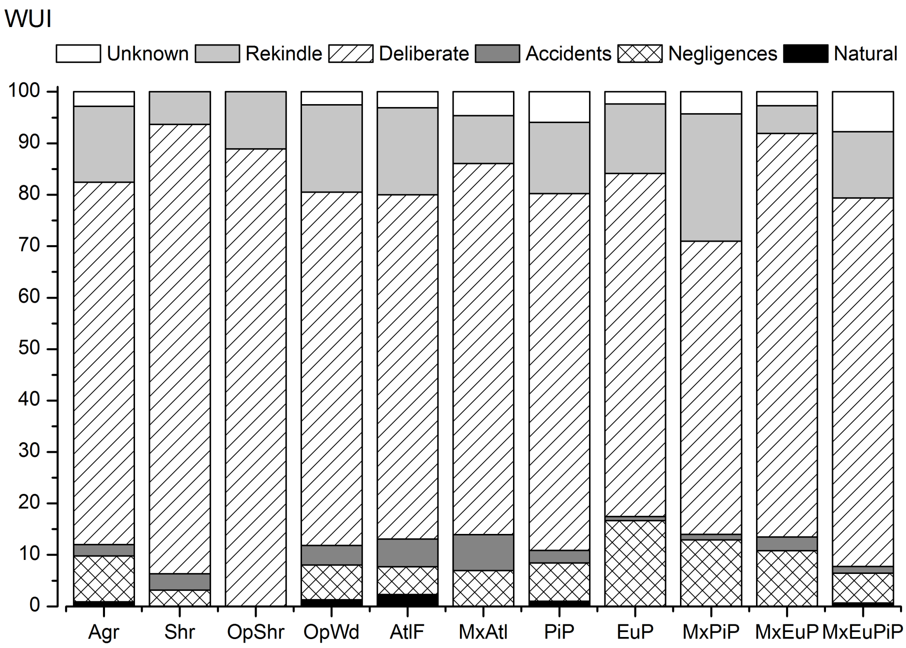


Fig. 3: Total area burned in fires with different causes in non WUI (white boxes) and WUI areas (grey boxes). Means and percentiles are represented as in Fig. 2. Causes are arranged according to mean fires sizes for pooled data (WUI and non WUI), in descending order.



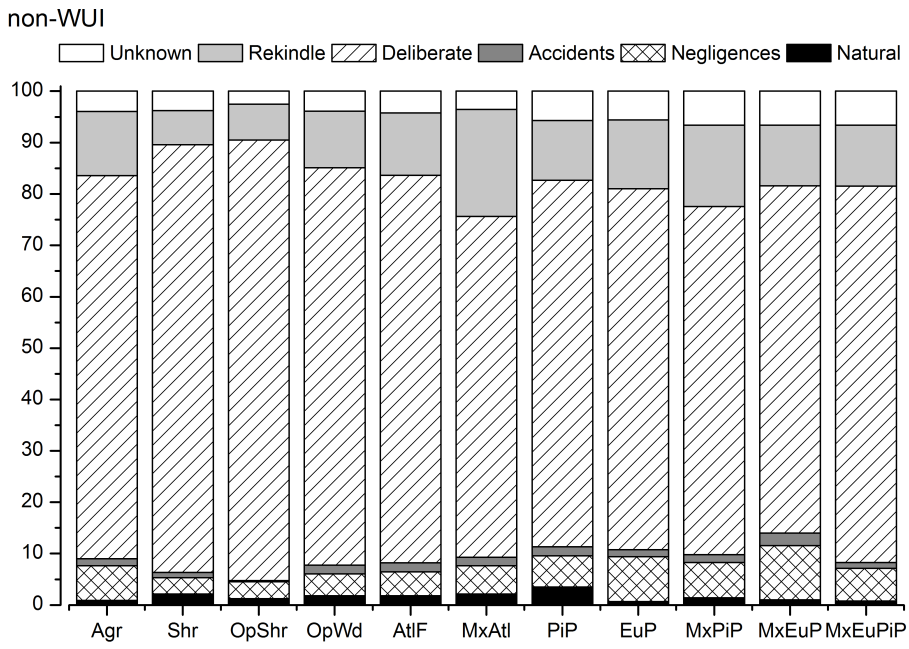


Fig. 4: Percentage of fires with different causes in each LULC type in WUI and non-WUI areas.

4. Discussion

4.1. The risk of ignition

Consistently with previous literature, there was a clear effect of the WUI on the risk of fire ignition (e.g., Lampin-Maillet et al 2011; Herrero et al 2012; Chas-Amil et al 2013, 2015). The risk of fire was also affected by LULCs (see also e.g., Bajocco and Ricotta 2008; Guglietta et al 2015) and, interestingly, there was an interaction between these factors: i.e., the pattern of fire risk associated with different LULCs differed between WUI and non-WUI areas.

Increased ignition risk in WUIs is the result of the proximity of human settlements that affects the type of activities in the surrounding landscape (Bar-Massada et al 2014). The remarkable differences found between WUI and non-WUI areas in the relative fire risk of different LULCs (interaction WUI : LULC), particularly important for forestry plantations, have important implications for management. Although the great majority of fires have human related causes in the study region, the intrinsic characteristics of vegetation related to its flammability should be also considered as important determinants of fire risk, since flammability determines the consequence of the accident, negligence or even the success of a deliberate attempt to set a fire. Forestry plantations (especially those with pines), shrublands and open woodlands showed the highest ignition risk in WUI, which may be explained by the high flammability of these land covers, which results in a disproportionate increase of the risk of ignition when the density of human population and, consequently, the intensity of use increases. Pines and eucalypts, the trees most frequently used by the forestry industry (mostly *P. pinaster* and *E. globulus*), have some characteristics that increase their flammability: e.g., high content in flammable volatile essential oils, high leaf surface area-to-volume ratio, which facilitates water loss and heat absorption, or high light penetration of their canopies, which allows more heat reaching the ground and increases moisture loss (Dimitrakopoulos and Papaioannou 2001; Schwilk and Ackerly 2001). The risk of ignition in forestry plantations decreased moderately outside the WUI, where human density is lower, although this trend was less marked in mixed plantations with pines or with pines and eucalypts.

However, in shrublands, where fire causes are more related with management activities, especially in relation to ranching outside the WUI (e.g. pastoral burnings; results not shown), the proximity to human settlements had less influence on ignition risk, that remained high outside the WUI. Shrublands are used for extensive livestock grazing and deliberate periodical burnings have been traditionally practiced to provide a flush of new growth more nutritious for grazers (Webb 1998), which contributes to the high percentage of deliberate fires in this land cover (the highest among all LULCs). The high fire-proneness of shrublands has been also shown in previous studies (see e.g. Nunes et al 2005; González and Pukkala 2007; Moreira et al 2009; Wittenberg and Malkinson 2009; Marques et al 2011; Oliveira et al 2013; Barros and Pereira 2014; Pereira et al 2014). This has been attributed to large amounts of fuel, close to the ground and of highly flammable species (such as *Ulex spp*., or *Erica spp*., Baeza et al 2002). The high flammability and fast regeneration capabilities after fire of shrublands may lead to positive feedbacks, which favour shrubland expansion and the incidence of fire (e.g., Paritsis et al 2015). Positive feedbacks have also been related to Acacia woods (Mandle et al 2011), which showed very high ignition risk and are recognized as highly invasive in this region (e.g., González-Muñoz et al 2012; Touza et al 2014). A positive relationship between their spread and fire incidence has been reported, i.e., areas currently occupied by acacias have often been previously affected by fire (Hernández et al 2014).

It is remarkable the low ignition risk of native forests (both AtlF and MedF) compared to plantations, especially plantations with pines (mostly *P. pinaster*), that showed higher risk than those with eucalypts (mostly *E. globulus*). This pattern among forested land covers agrees with the findings of previous studies (e.g., Silva et al 2009; Moreira et al 2009, 2011). Native forests showed the lowest fire risk of all land covers outside the WUI. Ignition risk in native forests increased with increasing human presence in the WUI, but remained low compared to other LULCs (except for Agr). AtlF, the most abundant native forest type in the region, is characterized by the deep shade provided by canopies. This favours low temperatures and high moisture contents, and limits the amount of biomass growing in the understory, compared to eucalypt or pine plantations (Calviño-Cancela et al 2012), all contributing to reduce fire risk.

Ignition risk was also low in Agr (see also e.g., Nunes et al 2005; Carmo et al 2011). Although most fires started in Agr, this LULC also occupies a large proportion of the land, especially in the WUI (70%), and the number of fires recorded, although large, was lower than expected for such a frequent LULC. This reduced fire risk is probably due to reduced fuel loads and the close attention paid by farmers to their valued crops, especially within the WUI. This can explain the lower fire risk in WUI compared to non-WUI areas, the only LULC where this occurred.

4.2. The risk of fire spread

There was also a clear effect of the WUI on the risk of fire spread (lower risk of spread in WUIs, consistently with Spyratos et al 2007 and Lampin-Maillet et al 2011). Even though there were significant interactions between the effect of the WUI and those of LULCs and fire causes, the general trend of lower risk of spread in WUIs applied to all LULCs and causes.

The smaller risk of spread in the WUI contrasts with the higher risk of ignition in these areas. The higher population density within the WUI favours earlier fire detection which, together with a better accessibility of these areas for fire-fighting brigades, translates into a quicker response within WUIs. In addition, WUIs are of greater priority for firefighters for the important economic and social consequences that a large fire may cause in WUIs (Moreira et al 2009; Barros and Pereira 2014). Thus, earlier detection, more intense suppression efforts as well as a better accessibility, all contribute to reduce the size of fires within the WUI. In addition, vegetation within the WUI is more fragmented (Chas-Amil et al 2013), and fuel discontinuity contributes to limit the spread of fire (Syphard et al 2007).

Agricultural lands show the smallest difference in the size of fires between WUI and non-WUI. This result may be related to their low flammability and high attention paid by their owners, which results in small fires even outside the WUI. On the contrary, in shrublands, the high flammability and high proportion of deliberate fires, which are associated to larger burned areas, contribute to a high risk of fire spread in this LULC. This risk is higher especially outside the WUI, where fire control is more difficult. Moreover, shrublands are often perceived as having low value, by the general public and also by firefighters, and this might reduce the priority of this land cover for firefighting operations (Moreira et al 2009). There was a lower risk of fire spread in native forests (AtlF and MxAtl) compared to tree plantations when looking at average sizes of burned areas. This result is consistent with that found in relation to fire ignition.

The higher risk of fire spread related to deliberate fires reflects the success of arsonists in achieving the goal pursued. They usually aim to cause the greatest damage. For instance, they use fire accelerants such as gasoline, act on days with favourable conditions for fire (hot and windy days) or in late hours to make it difficult for aerial resources to combat the fire (e.g., Prestemon and Butry 2008; Prestemon et al 2012). Rekindle fires were even larger on average, for the influence on the mean of very large fires. In this case, the conditions that favour the re-start of a fire after it had been apparently controlled also favour fire spread in large areas before it can be safely controlled. In addition, rekindle fires show the largest difference in fire sizes between WUI and non-WUI areas, which points to the success of fire fighting measures in WUI and the higher priority of these areas for fire control.

4.3. Implications for land management

Fire prevention and management in Spain focuses on reducing fuel loads (MAGRAMA 2012). Vegetation clearing is carried out by both public entities and private owners, who are compelled to clear natural vegetation in WUIs. This requires the continuous removal of vegetation in a battle against natural succession, which is costly and hardly sustainable in the long term. Alternatively, promotion of land covers with low fire risk should be considered as a low cost option for some areas, which would be more sustainable in the long term.

In this regard, the low fire risk showed by native forests is striking and should be taken into account by forest managers for fire hazard control purposes. Well preserved native forests can be seen as a natural protection against fire in this region, as natural succession leads to their spontaneous establishment in many areas (up to 550-600 m.a.s.l., Izco 1987). In addition, native forests harbour richer and more distinctive communities than forestry plantations, thus making an important contribution to the maintenance of regional biodiversity (Calviño-Cancela et al 2012, 2013, Calviño-Cancela 2013). Native forests regenerate naturally and are quite resistant to alien plant invasions (Martin et al 2009; Calviño-Cancela and Rubido-Bará 2013), thus requiring low or no human intervention. This is in clear contrast with agricultural areas, which showed also low fire risk but require continuous management efforts.

Agricultural abandonment, a pervasive trend in rural areas in Europe, has led to a significant increment in fuel accumulation in the landscape, especially in WUI areas, increasing fire risks (Moreira et al 2001). Land abandonment is predicted to continue in the next decades (Verburg and Overmars 2009), despite European Union subsidies to fight against this trend (under the European Common Agricultural Policy). Abandoned croplands lead firstly to shrublands, which show high risk of fire. However, in the absence of major disturbances, succession ultimately leads to the establishment of native broadleaf forests in most areas in the study region (Izco 1987), with low fire risk and management costs. Meanwhile, especial attention to avoid fire would be required in order to overcome the shrubland stage of high fire risk.

The abandonment of agricultural activities has frequently led to other, less intensive, uses, such as low-management forestry. The expansion of plantations in many parts of Galicia, especially those of *Eucalyptus globulus*, sometimes at the expense of broadleaved forests (Marey-Pérez et al 2006), may have contributed to increase the fire hazard in this region. The high flammability and post-fire regeneration capabilities of pines and eucalypts can promote positive feedbacks (Schwilk and Ackerly 2001; Mandle et al 2011) that favour their spread in other types of vegetation, including native forests (Calviño and Rubido-Bará 2013). This promotes the expansion of mixed formations (MxAtlF, MxPiP, MxEuP, MxEuPiP), which showed more fire proneness. The higher fire risk of mixed compared to more pure plantations might be due to differences in fuel due to poor forestry management. Plantations in this region are established as monocultures, mostly of *E. globulus* or *P. pinaster*, therefore mixed formations dominated by these trees are the result of poor management or abandonment, frequently after harvest or fire, leading to the natural establishment of a variety of species. Inadequate management occurs because most plantations in this region are small and privately owned by individuals or communities (the average land property per individual owner is 1.5 - 2 ha, and 80% of parcels are smaller than 0.5 ha; GEPC 2006). In contrast, plantations managed by the paper industry (c. 11,000 ha, ENCE 2013) typically have an intensive management, with frequent removal of the understory, often with the use of herbicides. Although this has obvious negative impacts for biodiversity, it surely reduces fuel loads and thus fire risk.

In abandoned areas where the management required for forestry plantations is hardly carried out, often leading to low-profitable and fire prone mixed formations, rewilding with native forests may constitute a low cost alternative, more sustainable in the long term than a subsidized maintenance of agricultural practices to keep fuel loads under leash (Navarro and Pereira 2012).

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