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

CrossMark

María Calviño-Cancela [a,*], María L. Chas-Amil [b], Eduardo D. García-Martínez [c], Julia Touza [d]

[a] Department of Ecology and Animal Biology, University of Vigo, Experimental Sciences Building, University Campus, 36310 Vigo, Spain
[b] Departamento de Economía Cuantitativa, Universidade de Santiago de Compostela, Baixada Burgo das Nacións s/n, 15782 Santiago de Compostela, Spain
[c] Department of Geology Geography and Environment, University of Alcalá de Henares, Calle Colegios 2, 28801 Alcalá de Henares, Spain
[d] Environment Department, University of York, Wentworth Way, Heslington, YO105NG York, UK

ARTICLE INFO

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 analyse 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 × 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.

© 2016 Elsevier B.V. All rights reserved.

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-Corral 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 4500 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 18 °C and January the coldest with 7 °C.

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 2442 km² 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 km² and a population of 2,747,559 people (2014; population density = 92.9 people per km²), Galicia is characterized by a very disperse population, even though nearly half of the population live in highly populated areas (3317 people per km²; 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

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

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.

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.

2.3. Data analyses

We selected 26,838 random locations in the region (the same number as fires recorded) to analyse 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 5000 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 × 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.

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 71–75)	25.8	73.9
Grasslands	Gra	Natural vegetation dominated by grasses and forbs (classified as herbaceous vegetation in IFN4 structural types; codes 31–33)	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

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).

3.2. The risk of fire spread

The area burned per fire was very variable, from less than 0.01 ha up to 7352 ha, with an average size of 6.7 ha. Data overdispersion (variances larger than means) was apparent in regard to fire sizes (Figs. 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,

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		

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 75th and 90th 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).

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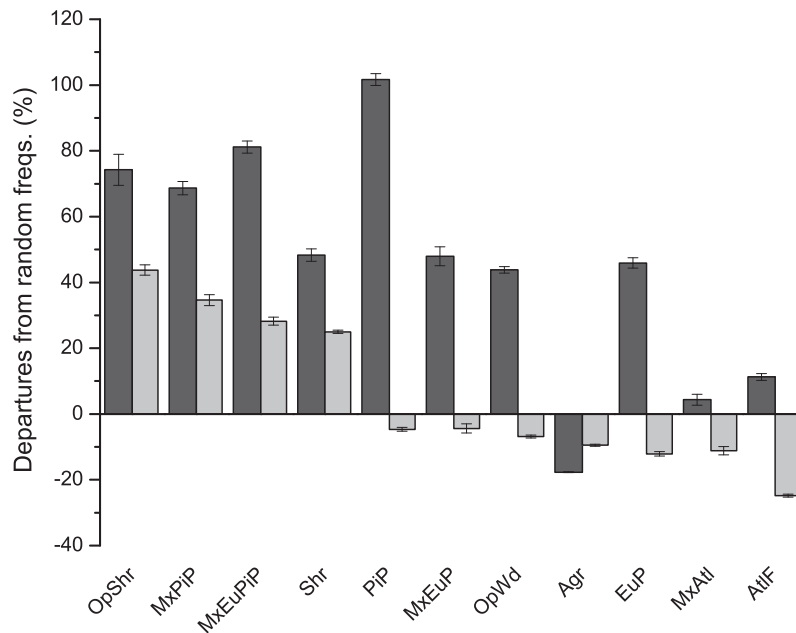
Fig. 1. Percent differences between the number of fires recorded and those expected according to a random distribution among the available LULCs types, in WUI (dark grey) and non-WUI (light grey) areas. LULCs are arranged in descending order in terms of fire risk with WUI and non-WUI areas pooled.
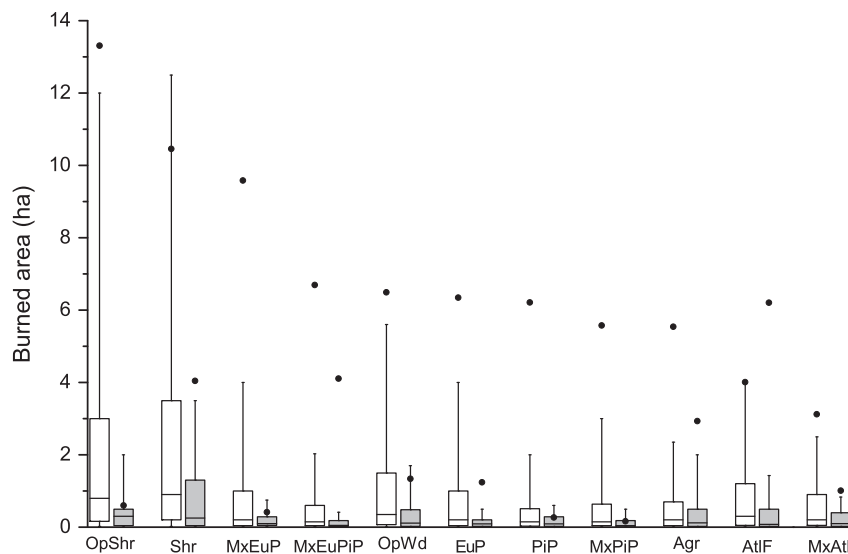

Fig. 2. Total area burned in fires ignited in different LULCs in non WUI (white boxes) and WUI (grey boxes) areas. Means are represented with filled circles; boxes extend from the 25th and 75th percentiles, with medians in the inner horizontal line, and whiskers show the 10th and 90th percentiles. Land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

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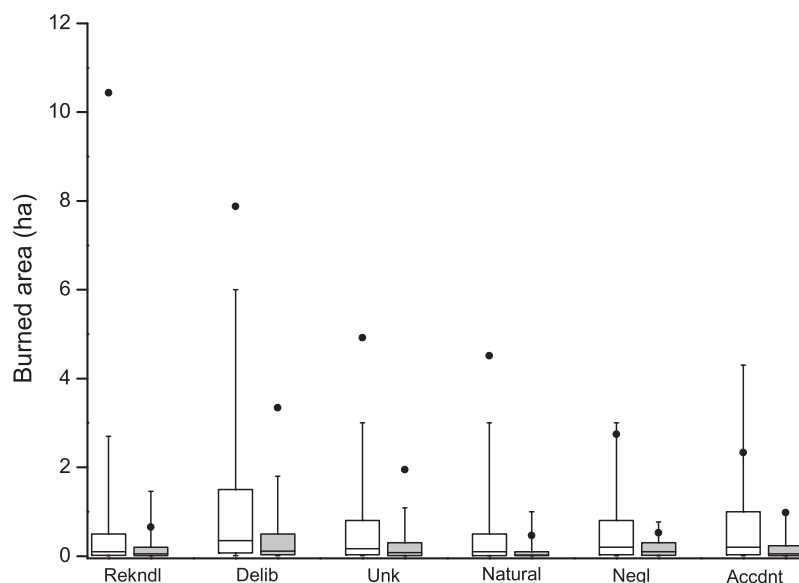
Fig. 3. Total area burned in fires with different causes in non WUI (white boxes) and WUI areas (grey boxes). Means and percentiles are represented as in Fig. 2. Causes are arranged according to mean fires sizes for pooled data (WUI and non WUI), in descending order.

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

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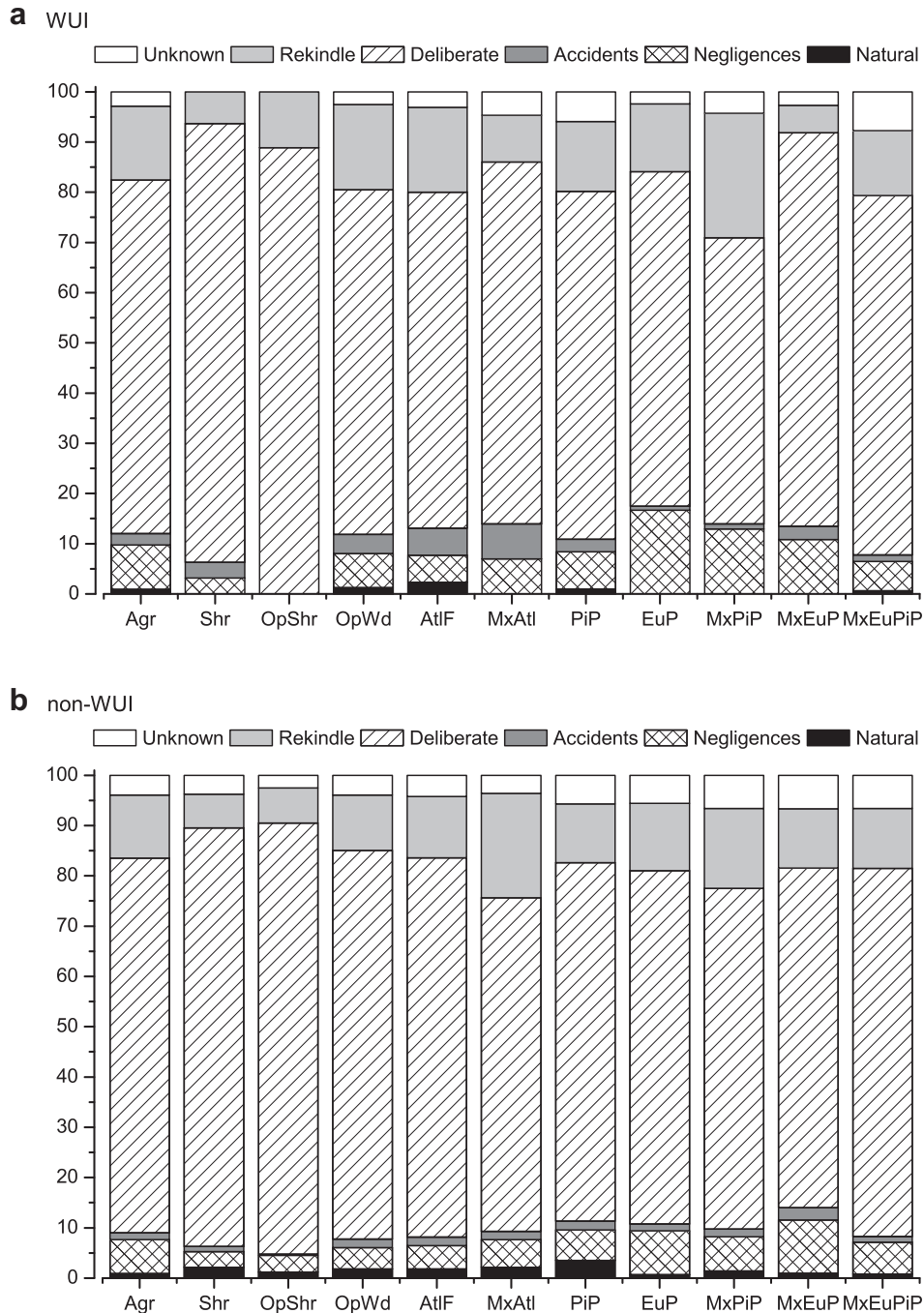
Fig. 4. Percentage of fires with different causes in each LULC type in WUI and non-WUI areas.

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 *E. 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-Cancela 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).

Acknowledgments

References

Baeza, M.J., De Luis, M., Raventós, J., Escarré, A., 2002. Factors influencing fire behaviour in shrublands of different stand ages and the implications for using prescribed burning to reduce wildfire risk. J. Environ. Manage. 65, 199–208.
Bajocco, S., Ricotta, C., 2008. Evidence of selective burning in Sardinia (Italy): which land-cover classes do wildfires prefer? Landscape Ecol. 23 (2), 241–248.
Bar-Massada, A., Radeloff, V.C., Stewart, S.I., 2014. Biotic and abiotic effects of human settlements in the wildland-urban interface. Bioscience 64 (5), 429–437.
Barros, A.M., Pereira, J.M., 2014. Wildfire selectivity for land cover type: does size matter? PLoS ONE 9, 684760.
Calviño-Cancela, M., Rubido-Bará, M., 2013. Invasive potential of *Eucalyptus globulus*: seed dispersal, seedling recruitment and survival in habitats surrounding plantations. For. Ecol. Manage. 305, 129–137.
Calviño-Cancela, M., Rubido-Bará, M., van Etten, E.J.B., 2012. Do eucalypt plantations provide habitat for native forest biodiversity? For. Ecol. Manage. 270, 153–162.
Calviño-Cancela, M., 2013. Effectiveness of eucalypt plantations as a surrogate habitat for birds. For. Ecol. Manage. 310, 692–699.
Calviño-Cancela, M., Eugenia Lopez de Silanes, M., Rubido-Bara, M., Uribarri, J., 2013. The potential role of tree plantations in providing habitat for lichen epiphytes. For. Ecol. Manage. 291, 386–395.
Cardille, J.A., Ventura, S.J., 2001. Occurrence of wildfire in the northern Great Lakes Region: effects of land cover and land ownership assessed at multiple scales. Int. J. Wildland Fire 10, 145–154.
Carmo, M., Moreira, F., Casimiro, P., Vaz, P., 2011. Land use and topography influences on wildfire occurrence in northern Portugal. Landscape Urban Plann. 100, 169–176.
Chas-Amil, M.L., Prestemon, J.P., McClean, C., Touza, J., 2015. Human-ignited wildfire patterns and responses to policy shifts. Appl. Geogr. 5, 164–176.
Chas-Amil, M.L., Touza, J., García-Martínez, E., 2013. Forest fires in the wildland-urban interface: a spatial analysis of forest fragmentation and human impacts. Appl. Geogr. 43, 127–137.
Chas-Amil, M.L., Touza, J., Prestemon, J.P., 2010. Spatial distribution of human-caused forest fires in Galicia (NW Spain). In: Perona, G., Brebbia, C.A. (Eds.), Modelling, Monitoring and Management of Forest Fires. WIT Press, pp. 247–258.
Cramer, V.A., Hobbs, R.J. (Eds.), 2007. Old Fields: Dynamics and Restoration of Abandoned Farmland. Island Press, Washington D.C, ISBN: 978-1-5972-6074-9.
Cumming, S.G., 2001. Forest type and wildfire in the Alberta boreal mixedwood: what do fires burn? Ecol. Appl. 11, 97–110.
Díaz-Maroto, I.J., Vila-Lameiro, P., 2008. Historical evolution and land-use changes in natural broadleaved forests in the north-west Iberian Peninsula. Scand. J. For. Res. 23, 371–379.
Dimitrakopoulos, A.P., Papaioannou, K.K., 2001. Flammability assessment of Mediterranean forest fuels. Fire Technol. 37, 143–152.
ENCE, 2013. Informe sobre la contribución de Ence Pontevedra al desarrollo social, económico y ambiental de Galicia. 36 p.
European Commission, 2014. Forest Fires in Europe, Middle East and North Africa 2013. EUR 26791 EN.
FAO, 2007. Fire management-Global assessment 2006. FAO Forestry Paper 151. Rome.
FAO, 2010. Global Forest Resources Assessment 2010. FAO Forestry Paper 163. Rome.
Foley, J.A., DeFries, R., Asner, G.P., et al., 2005. Global consequences of land use. Science 309 (5734), 570–574.
GEPC (Grupo de Estudo da Propiedade Comunal), 2006. Os montes veciñais en man común: O patrimonio silente. Natureza, economía, identidade e democracia na Galicia rural. Ed. Xerais de Galicia, Vigo.
González, J.R., Pukkala, T., 2007. Characterization of forest fires in Catalonia (north-east Spain). Eur. J. Forest Res. 126, 421–429.
González-Muñoz, N., Costa-Tenorio, M., Espigares, T., 2012. Invasion of alien *Acacia dealbata* on Spanish *Quercus robur* forests: Impact on soils and vegetation. For. Ecol. Manage. 269, 214–221.
Guglietta, D., Migliozzi, A., Ricotta, C., 2015. A multivariate approach for mapping fire ignition risk: the example of the National Park of Cilento (Southern Italy). Environ. Manage. 56, 157–164.
Hardy, C.C., 2005. Wildland fire hazard and risk: problems, definitions, and context. For. Ecol. Manage. 211, 73–82.
Hernández, L., Martínez-Fernandez, J., Canellas, I., Vázquez de la Cueva, A., 2014. Assessing spatio-temporal rates, patterns and determinants of biological invasions in forest ecosystems. The case of Acacia species in NW Spain. For. Ecol. Manage. 329, 206–213.
Herrero-Corral, G., Jappiot, M., Bouillon, C., Long-Fournel, M., 2012. Application of a geographical assessment method for the characterization of wildland-urban interfaces in the context of wildfire prevention: a case study in western Madrid. Appl. Geogr. 35, 60–70.
IGE (Instituto Galego de Estatística), 2011. Clasificación do grao de urbanización das parroquias e dos concellos galegos.
Izco, J., 1987. Galicia. In: Alcaraz, F. et al. (Eds.), La vegetación en España. Universidad de Alcalá de Henares.
Jappiot, M., Gonzales-Olabarria, J.R., Lampin-Maillet, C., Borgniet, L., 2009. Assessing wildfire risk in time and space. In: Birot, Y. (Ed.), Living with Wildfires: What science can tell us? A Contribution to the Science-policy Dialogue. European Forest Institute, pp. 41–47.
Lambin, E.F., Turner, B.L., Geist, H.J., et al., 2001. The causes of land-use and land-cover change: moving beyond the myths. Global Environ. Change-Human Policy Dimensions 11 (4), 261–269.
Lampin-Maillet, C., Long-Fournel, M., Ganteaume, A., Jappiot, M., Ferrier, J.P., 2011. Land cover analysis in wildland-urban interfaces according to wildfire risk: a case study in the South of France. For. Ecol. Manage. 261, 2200–2213.
MAGRAMA, 2011a. Cuarto Inventario Forestal Nacional. Galicia. [DVD]. Ministerio de Agricultura, Alimentación y Medio Ambiente.

MAGRAMA, 2011b. Mapa Forestal de España 1:25,000.

MAGRAMA, 2012. Los incendios forestales en España. Decenio 2001–2010 (Madrid: Ministerio de Medio Ambiente. Centro de Coordinación de la Información Nacional sobre Incendios Forestales).

Mandle, L., Bufford, J.L., Schmidt, I.B., Daehler, C.C., 2011. Woody exotic plant invasions and fire: reciprocal impacts and consequences for native ecosystems. Biol. Invasions 13, 1815–1827.

Manuel, C., Gil, L., 2002. La transformación histórica del paisaje forestal en Galicia. Tercer Inventario Forestal Nacional. Ministerio de Medio Ambiente, Madrid, Spain.

Marey-Pérez, M.F., Rodríguez-Vicente, V., Crecente-Maseda, R., 2006. Using GIS to measure changes in the temporal and spatial dynamics of forestland, experiences from North-West Spain. Forestry 79, 409–423.

Marques, S., Borges, J.G., Garcia-Gonzalo, J., Moreira, F., Carreiras, J.M.B., Oliveira, M., Cantarinha, A., Botequim, B., Pereira, J.M.C., 2011. Characterization of wildfires in Portugal. Eur. J. For. Res. 130, 775–784.

Martin, P.H., Canham, C.D., Marks, P.L., 2009. Why forests appear resistant to exotic plant invasions: intentional introductions, stand dynamics, and the role of shade tolerance. Front. Ecol. Environ. 7, 142–149.

Martínez, J., Vega-García, C., Chuvieco, E., 2009. Human-caused wildfire risk rating for prevention planning in Spain. J. Environ. Manage. 90, 1241–1252.

Mermoz, M., Kitzberger, T., Veblen, T.T., 2005. Landscape influences on occurrence and spread of wildfires in Patagonian forests and shrublands. Ecology 86 (10), 2705–2715.

Montiel, C., Herrero, G., 2010. Overview of policies and practices related to fire ignitions. In: Sande, J. (Ed.), Towards Integrated Fire Management-outcomes of the European Project Fire Paradox. European Forest Institute, pp. 35–46.

Moreira, F., Rego, F.C., Ferreira, P.G., 2001. Temporal (1958–1995) pattern of change in a cultural landscape of northwestern Portugal: implications for fire occurrence. Landscape Ecol. 16, 557–567.

Moreira, F., Vaz, P., Catry, F., Silva, J.S., 2009. Regional variations in wildfire susceptibility of land-cover types in Portugal: implications for landscape management to minimize fire hazard. Int. J. Wildland Fire 18, 563–574.

Moreira, F., Viedma, O., Arianoutsou, M., Curt, T., Koutsias, N., Rigolot, E., Barbati, A., Corona, P., Vaz, P., Xanthopoulos, G., Mouillot, F., Bilgili, E., 2011. Landscape–wildfire interactions in southern Europe: implications for landscape management. J. Environ. Manage. 92 (10), 2389–2402.

Navarro, L.M., Pereira, H.M., 2012. Rewilding abandoned landscapes in Europe. Ecosystems 15 (6), 900–912.

Nunes, M.C.S., Vasconcelos, M.J., Pereira, J.M.C., Dasgupta, N., Alldredge, R.J., Rego, F. C., 2005. Land-cover type and fire in Portugal: do fires burn land cover selectively? Landscape Ecol. 20, 661–673.

Oliveira, S., Moreira, F., Boca, R., San-Miguel-Ayanz, J., Pereira, J.M.C., 2013. Assessment of fire selectivity in relation to land cover and topography: a comparison between Southern European countries. Int. J. Wildland Fire 23 (5), 620–630.

Padilla, M., Vega-García, C., 2011. On the comparative importance of fire danger rating índices and their integration with spatial and temporal variables for predicting daily human-caused fire occurrences in Spain. Int. J. Wildland Fire 20, 46–58.

Paritsis, J., Veblen, T.T., Holz, A., 2015. Positive fire feedbacks contribute to shifts from *Nothofagus pumilio* forests to fire-prone shrublands in Patagonia. J. Veg. Sci. 26, 89–101.

Pereira, M.G., Aranha, J., Amraoui, M., 2014. Land cover fire proneness in Europe. For. Syst. 23, 598–610.

Prestemon, J.P., Butry, D.T., 2008. Wildland arson management. In: Holmes, T.P. et al. (Eds.), The Economics of Forest Disturbances: Wildfires, Storms, and Invasive Species. Springer, pp. 123–147.

Prestemon, J.P., Chas-Amil, M.L., Touza, J., Goodrick, S.J., 2012. Forecasting intentional wildfires using temporal and spatio-temporal autocorrelations. Int. J. Wildland Fire 21 (6), 743–754.

Ramil-Rego, P., Muñoz-Sobrino, C., Rodríguez-Guitián, M., Gómez-Orellana, L., 1998. Differences in the vegetation of the north Iberian Peninsula during the last 16,000 years. Plant Ecol. 138, 41–62.

Rego, F.C., Silva, J.S., 2014. Wildfires and landscape dynamics in Portugal: a regional assessment and global implications. In: Azevedo, J.C., Perera, A.H., Pinto, M.A. (Eds.), Forest Landscapes and Global Change. Springer, New York, pp. 51–73.

Saura-Mas, S., Paula, J., Pausas, J.G., Lloret, F., 2010. Fuel loading and flammability in the Mediterranean Basin woody species with different post-fire regenerative strategies. Int. J. Wildland Fire 1, 783–794.

Schwilk, D.W., Ackerly, D.D., 2001. Flammability and serotiny as strategies: correlated evolution in pines. Oikos 94, 326–336.

Sebastián-López, A., Salvador-Civil, R., Gonzalo-Jiménez, J., San Miguel-Ayanz, J., 2008. Integration of socio-economic and environmental variables for modelling long-term fire danger in Southern Europe. Eur. J. Forest Res. 127, 149–163.

Silva, J.S., Moreira, F., Vaz, P., Catry, F., Godinho-Ferreira, P., 2009. Assessing the relative fire proneness of different forest types in Portugal. Plant Biosyst. 143 (3), 597–608.

Spyratos, V., Bourgeron, P.S., Ghil, M., 2007. Development at the wildland–urban interface and the mitigation of forest-fire risk. Proc. Natl. Acad. Sci. 104, 14272–14276.

Syphard, A.D., Radeloff, V.C., Keeley, J.E., Hawbaker, T.J., Clayton, M.K., Stewart, S.I., 2007. Human influence on California fire regimes. Ecol. Appl. 17 (5), 1388–1402.

Teixido, A.L., Quintanilla, L.G., Carreno, F., Gutiérrez, D., 2010. Impacts of changes in land use and fragmentation patterns on Atlantic coastal forests in northern Spain. J. Environ. Manage. 91 (4), 879–886.

Theobald, D.M., Romme, W., 2007. Expansion of the US wildland-urban interface. Landscape Urban Plann. 83 (4), 340–354.

Touza, J., Pérez-Alonso, A., Chas-Amil, M.L., Dehnen-Schumtz, K., 2014. Explaining the rank order of invasive plants by stakeholder groups. Ecol. Econ. 105, 330–341.

Verburg, P.H., Overmars, K.P., 2009. Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. Landscape Ecol. 24, 1167–1181.

Webb, N.R., 1998. The traditional management of European heathlands. J. Appl. Ecol. 35, 987–990.

Wittenberg, L., Malkinson, D., 2009. Spatio-temporal perspectives of forest fires regimes in a maturing Mediterranean mixed pine landscape. Eur. J. Forest Res. 128 (3), 297–304.