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Calviño-Cancela, María, Chas-Amil, María L., García-Martínez, Eduardo et al. (1 more author) (2016) Wildfire risk associated with different vegetation types within and outside wildland-urban interfaces. *Forest Ecology and Management*. pp. 1-9. ISSN 0378-1127

<https://doi.org/10.1016/j.foreco.2016.04.002>

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

3 María Calviño-Cancela • María L. Chas-Amil • Eduardo D. García-Martínez • Julia Touza

4

5 M. Calviño-Cancela (corresponding author)

6 Department of Ecology and Animal Biology, University of Vigo.

7 Experimental Sciences Building. University Campus. 36310 Vigo, Spain

8 [maria@uvigo.es](mailto:maria@uvigo.es); Phone: +34 986 818 742

9 M. L. Chas-Amil

10 Departamento de Economía Cuantitativa, Universidade de Santiago de Compostela.

11 Baixada Burgo das Nacións s/n. 15782 Santiago de Compostela, Spain; [marisa.chas@usc.es](mailto:marisa.chas@usc.es)

12 E. D. García-Martínez

13 Department of Geology Geography and Environment, University of Alcalá de Henares.

14 Calle Colegios 2. 28801. Alcalá de Henares, Spain; [edgm\\_73@yahoo.es](mailto:edgm_73@yahoo.es)

15 J. Touza

16 Environment Department, University of York.

17 Wentworth Way, Heslington, YO105NG, York, UK; [julia.touza@york.ac.uk](mailto:julia.touza@york.ac.uk)

18

19

20 **Abstract**

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

30 The aim of this study is to assess the effect of the WUI on fire ignition risk and the area  
31 burned, and the interaction between its effect and that of the LULC. We used a database of  
32 26,838 wildfires recorded in 2006-2011 in NW Spain and compared fire patterns in relation to  
33 WUI and LULC with a random model, using a Montecarlo approach.

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

43 The differences found between LULCs in fire risk, both in WUI and non-WUI areas, have  
44 interesting implications for fire management. Promotion of land covers with low fire risk

45 should be considered as a low cost alternative to the usual fire prevention measures based on  
46 fuel load reduction, which require the continuous clearing of vegetation. In this regard, the low  
47 fire risk in native forests should be taken into account. Native forests naturally colonize many  
48 areas in the study region and require low or no management, in contrast with agricultural areas,  
49 also with low fire risk but requiring continuous management in order to avoid colonization by  
50 natural vegetation.

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

52

### 53 **Abbreviations**

54 WUI: Wildland-urban interface

55 LULC: land cover/land use

56 Agr: Agriculture areas

57 Gra: Grasslands

58 OpShr: Open shrublands

59 Shr: Shrublands

60 OpWd: Open woodlands

61 AtlF: Atlantic forests

62 MedF: Mediterranean forests

63 PiP: Pine plantations

64 EuP: Eucalypt plantations

65 Aca: Acacia woods

66 MxAtl: Mixed Atlantic forests

67 MxEuPiP: Mixed plantations of pines and eucalypts

68 MxPiP: Mixed pine plantations

69 MxEuP: Mixed eucalypt plantations

70

## 71 **1. Introduction**

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

87 When and where wildfires would occur is the result of complex interactions among  
88 natural and human ignition sources, weather, topography and land cover (e.g., Mermoz et al  
89 2005; Moreira et al 2011). Worldwide, landscapes are increasingly humanized with land cover  
90 changes being pervasive (e.g. the conversion of forests to croplands and tree plantations in  
91 developing areas or the expansion of forested land in areas of rural abandonment; Lambin et al  
92 2001; Foley et al 2005). Land use/land cover (LULC) has been shown to have a key role on  
93 fire risk (e.g., Cumming 2001; Nunes et al 2005; Bajocco and Ricotta 2008; Carmo et al 2011),  
94 as it determines fuel load and characteristics such as moisture content or horizontal and vertical  
95 fuel continuity (Saura-Mas et al 2010). For example, in Mediterranean areas, shrublands,

96 grasslands and coniferous forest were found to be more prone to fire than croplands and  
97 broadleaf forests (e.g., Oliveira et al 2013; Pereira et al 2014; Rego and Silva 2014).  
98 Understanding this selectivity of fire towards specific land cover types has been recognized as  
99 an essential background for policy making, since LULC, in contrast to other factors such as  
100 topography or weather, can be subject to active management. Moreover, as human-related  
101 causes (deliberate, negligent or accidental) are the most frequent causes of fires (FAO 2007),  
102 cultural, and socio-economic drivers can have a significant effect on the fire risk associated  
103 with certain LULCs (e.g., Cardille and Ventura 2001; Sebastián-López et al 2008; Martínez et  
104 al 2009; Marques et al 2011; Padilla and Vega-García 2011; Chas-Amil et al 2015). Since  
105 population density, human behaviour and activities differ markedly between WUI and non-  
106 WUI areas, human-related factors are expected to modify the risk of fire associated to LULCs  
107 depending on their location within or outside WUIs areas.

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

## 112 **2. Materials and methods**

### 113 **2.1. Study area**

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

122 (MAGRAMA 2012). In addition, most fires are human-caused (99%), and most are deliberate  
123 (75%) (Chas-Amil et al 2010).

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

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

139 Based on Chas-Amil et al (2013), the WUI totals 2,442 km<sup>2</sup> in Galicia, which represents  
140 8.3%, with a higher concentration along the Atlantic coast and in the southwest, where dense  
141 and very dense clustered building structures predominate. The WUI is characterized by a lower  
142 proportion of forested land compared to non-WUI areas (c. 20% vs. 75%), and has a higher  
143 level of forest fragmentation. With an area of 29,574.4 km<sup>2</sup> and a population of 2,747,559  
144 people (2014; population density = 92.9 people per km<sup>2</sup>), Galicia is characterized by a very  
145 disperse population, even though nearly half of the population live in highly populated areas  
146 (3,317 people per km<sup>2</sup>; IGE 2011). This high population dispersion together with the

147 exceptionally high incidence of fire makes the study of fire risks associated with the WUI  
148 especially relevant in this region.

## 149 **2.2 Data**

### 150 **2.2.1. Fire data**

151 This study used a database of 26,838 wildfire reports obtained from the Rural Affairs  
152 Department of the Regional Government (Xunta de Galicia), and the Spanish Ministry of  
153 Agriculture, Food and Environment (MAGRAMA) from the period January 1, 2006 to  
154 December 31, 2011. Forest fire reports list general information including location, date, burned  
155 areas and causes and motivations (Table 1). Only fires affecting wildland vegetation are  
156 included in this database. We evaluated the coordinates of fire ignition points by checking the  
157 agreement between those coordinates and the district and municipality given in fire reports,  
158 using topographic maps (National Topographic Map Series, IGN, scale 1:25,000), and the  
159 burned areas as visually identified in Landsat 5 TM images taken in different dates. When  
160 inconsistencies between these information sources were detected the point was discarded in  
161 most cases, or corrected when possible. All computations were performed with ArcGIS®  
162 10.2.2 by ESRI and Geomedia Professional 6.0 by Intergraph.

163 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.

164

165 **2.2.2. Wildland-urban interface**

166 According to the current fire-protection legislation in the region, the WUI was defined as the  
 167 area within a 50 m radius around buildings at a distance of up to 400 m from wildland  
 168 vegetation, where bush clearing is compulsory (Law 3/2007 of April 9, 2007, addressing the  
 169 issues of wildfire prevention and suppression, as modified by Law 7/2012 of June 28, 2012 of  
 170 Galician Forestry). The identification and mapping of WUIs in Galicia was obtained from  
 171 Chas-Amil et al (2013).

172 **2.2.3. Land cover**

173 For each fire ignition point we determined the land use/land cover type (LULC) using  
 174 information from the Fourth National Forest Inventory (IFN4, MAGRAMA 2011a), which is  
 175 based on the cartography of the Forest Map of Spain at 1:25,000 (MFE25, MAGRAMA  
 176 2011b). IFN4 defines the land use or vegetation in homogeneous polygons of 0.5 to 2 ha in  
 177 size (depending on cover type), according to a hierarchical classification of 63 land use types  
 178 and more than 200 types of vegetation communities. We modified this classification according  
 179 to our research interests, regrouping IFN4 classes into a total of 14 classes (Table 2), using  
 180 information from the IFN4 on the cover of trees, shrubs and herbs (grasses and forbs) and the  
 181 identity of the three dominant tree species and their relative dominance. Areas with no or very  
 182 scarce vegetation were excluded from the analyses (e.g., water bodies, beaches, or artificial  
 183 surfaces such as industrial or urban areas). The less frequent LULCs (i.e., grasslands,  
 184 Mediterranean forests and Acacia woods) were used only when WUI and non-WUI areas were

185 pooled, but were removed from analyses in which we distinguished between WUI and non-  
 186 WUI areas, due to the low number of fires in WUI in these categories.

187  
 188 Table 2. Description of the land cover categories used in this study, and the percentage of area  
 189 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 $\geq 60\%$ 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 $\geq 60\%$ tree cover				
Atlantic forests	AtlF	Native broadleaved forests typical of the Eurosiberian region, with $\geq 70\%$ dominance of <i>Quercus robur</i> , <i>Q. pyrenaica</i> , <i>Castanea sativa</i> , <i>Alnus glutinosa</i> , <i>Betula</i> spp., <i>Salix</i> spp., <i>Acer</i> spp., <i>Fraxinus</i> spp. or <i>Populus</i> spp.	10.8	4.0
Mediterranean forests	MedF	With $\geq 50\%$ dominance of <i>Q. ilex</i> or <i>Q. suber</i> .	0.1	0
Pine plantations	PiP	With $\geq 70\%$ dominance of <i>Pinus pinaster</i> , <i>P. sylvestris</i> , <i>P. radiata</i> or, rarely, other conifers.	9.1	3.4
Eucalypt plantations	EuP	With $\geq 70\%$ dominance of <i>Eucalyptus globulus</i> , or, more rarely, <i>E. nitens</i> or other eucalypts.	6.6	3.0

Acacia woods	Aca	With $\geq 50\%$ dominance of <i>Acacia dealbata</i> , mostly, <i>A. melanoxylon</i> 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 $\leq$ 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

190  
191 **2.3. Data analyses**  
192 We selected 26,838 random locations in the region (the same number as fires recorded)  
193 to analyze patterns of fire risk related to WUI and LULCs, using the module Random Points

194 Generation of Hawth's Analysis Tools, in ArcGIS. Random points were characterized in regard  
195 to WUI and LULCs (using the same criteria as for ignition points) in order to compare the  
196 patterns of fire distribution with a random model. We used a Montecarlo method  
197 (bootstrapping; random resampling with replacement), to obtain a total of 100 samples of  
198 5,000 points out of the 26,838 fire ignition and random points, respectively. We then calculated  
199 the proportional differences between the number of fires observed in each combination of  
200 LULCs x within/outside WUI and that in the random set, i.e., the expected number according  
201 to a random probability. Proportional differences were thus the observed minus the expected  
202 frequencies divided by the expected frequencies (this is analogous to selection indexes used in  
203 other studies; e.g., Moreira et al 2001; Bajocco and Ricotta 2008). We performed an ANOVA  
204 with LULC and within/outside WUI as fixed factors and the proportional differences between  
205 fire and random sets as the variate in order to analyse the patterns of fire ignition risk . Data on  
206 the size of wildfires had a negative binomial distribution, therefore, to analyse the effects of  
207 fire causes, the location of ignition points within/outside the WUI and the LULC on the size of  
208 burned areas we used a Generalized Linear Model with negative binomial distribution and  
209 logratio as link function. We previously estimated the aggregation parameter of the negative  
210 binomial distribution ( $k$ ) using the RNEGBINOMIAL procedure of GenStat 7th ed.

### 211 **3. Results**

#### 212 **3.1. The risk of ignition**

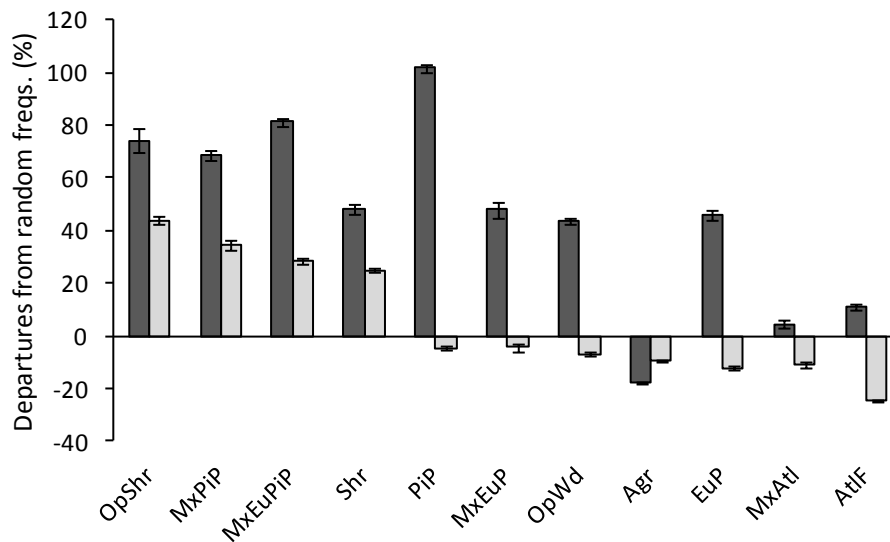
213 The risk of fire ignition in a particular location was significantly affected by the LULC type  
214 and the location within or outside the WUI ( $P < 0.001$ ; Table 3), with a significant interaction  
215 between these two factors ( $P < 0.001$ ; Table 3). This means that the pattern of ignition risk  
216 among LULCs differed between WUI and non-WUI areas (Fig. 1). The general trend was of  
217 higher ignition risk within the WUI for all LULCs except for Agr, with the opposite pattern.  
218 Pooling all LULCs, WUI registered 48% more fires than expected by random chance, in  
219 contrast with a 4% less than random chance in non-WUI areas. But this increased risk varied

220 widely in magnitude among LULCs, with PiP having the larger increment in WUI compared to  
 221 non-WUI (>100%) followed by EuP (58%), mixed plantations with eucalypts (MxEuPiP,  
 222 MxEuP; 52%), and OpWd (51%). Differences were smaller for AtlF, MxPiP and OpShr (36-  
 223 30%), and for Shr and MxAtl (23-16%). PiP, EuP, MxEuP and OpWd had more fires than  
 224 expected by random chance in WUI but slightly less outside the WUI, whereas AtlF had less  
 225 fires than expected by random chance outside the WUI (being the less fire prone LULC), but  
 226 slightly more than random within the WUI. Mixed plantations with pines (MxPiP and  
 227 MxEuPiP) and shrublands (Shr and OpShr) had more fires than expected by random both  
 228 within and outside the WUI. When pooling WUI and non-WUI areas, Acacia woods had the  
 229 highest fire risk (c. 100% more fires than expected), followed by Shrublands (both OpShr and  
 230 Shr) and Mixed pine plantations with eucalypts or other trees (MxEuPiP and MxPiP), that had  
 231 also more fires than expected by random (> 20% more). Native forests (both MedF and AtlF)  
 232 had the lowest ignition risk (16-25% less fires than expected).

233 Table 3: Results of the ANOVA on the effects of location within/outside the WUI and the  
 234 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		

235



236  
 237 Fig. 1: Percent differences between the number of fires recorded and those expected according  
 238 to a random distribution among the available LULCs types, in WUI (dark grey) and non-WUI  
 239 (light grey) areas. LULCs are arranged in descending order in terms of fire risk with WUI and  
 240 non-WUI areas pooled.

241 **3.2. The risk of fire spread**

242 The area burned per fire was very variable, from less than 0.01 ha up to 7,352 ha, with an  
 243 average size of 6.7 ha. Data overdispersion (variances larger than means) was apparent in  
 244 regard to fire sizes (Fig. 2 and 3), with means being larger than medians, 75<sup>th</sup> or even 90<sup>th</sup>  
 245 percentiles in many cases, due to the strong influence that very large fires had on means. Fire  
 246 causes, location of the ignition point within or outside the WUI as well as LULCs had all a  
 247 significant effect on the size of fires ( $P < 0.001$  in all cases; Table 4). There were also 2<sup>nd</sup> and  
 248 3<sup>rd</sup> level interactions between fire causes, location within or outside the WUI, and LULC ( $P <$   
 249  $0.03$  in all cases; Table 4), which indicates that the pattern of fire sizes among LULCs or  
 250 causes varied depending on location within or outside the WUI, although this difference was  
 251 less intense than for ignition risk (see above). In general, fires were smaller within the WUI  
 252 than outside (mean was  $2.7 \pm 0.5$  in WUI vs.  $7.2 \pm 0.5$  outside WUI, when pooling all LULCs,  
 253 and medians were 0.1 vs. 0.3, respectively). In Atlantic forests there was one single fire of 710

254 ha that had a great influence in the mean, making it larger (6.2 vs. 4.0), but fires were in  
 255 general smaller within the WUI (median size was 0.08 and 0.3 within and outside the WUI,  
 256 respectively. When pooling WUI and non-WUI areas, fires starting in shrublands were larger  
 257 than in other LULCs (OpShr and Shr; burned areas averaged 12.9 and 10.3 ha, respectively),  
 258 and those starting in tree plantations (mean fire sizes varied between 8.8 ha in MxEuP and 5.0  
 259 ha in MxPiP) were larger on average than those in agricultural areas (4.9 ha on average) and  
 260 Atlantic forests (4.2 and 2.9 ha in AtlF and MxAtl, respectively), which had the smallest  
 261 average sizes.

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

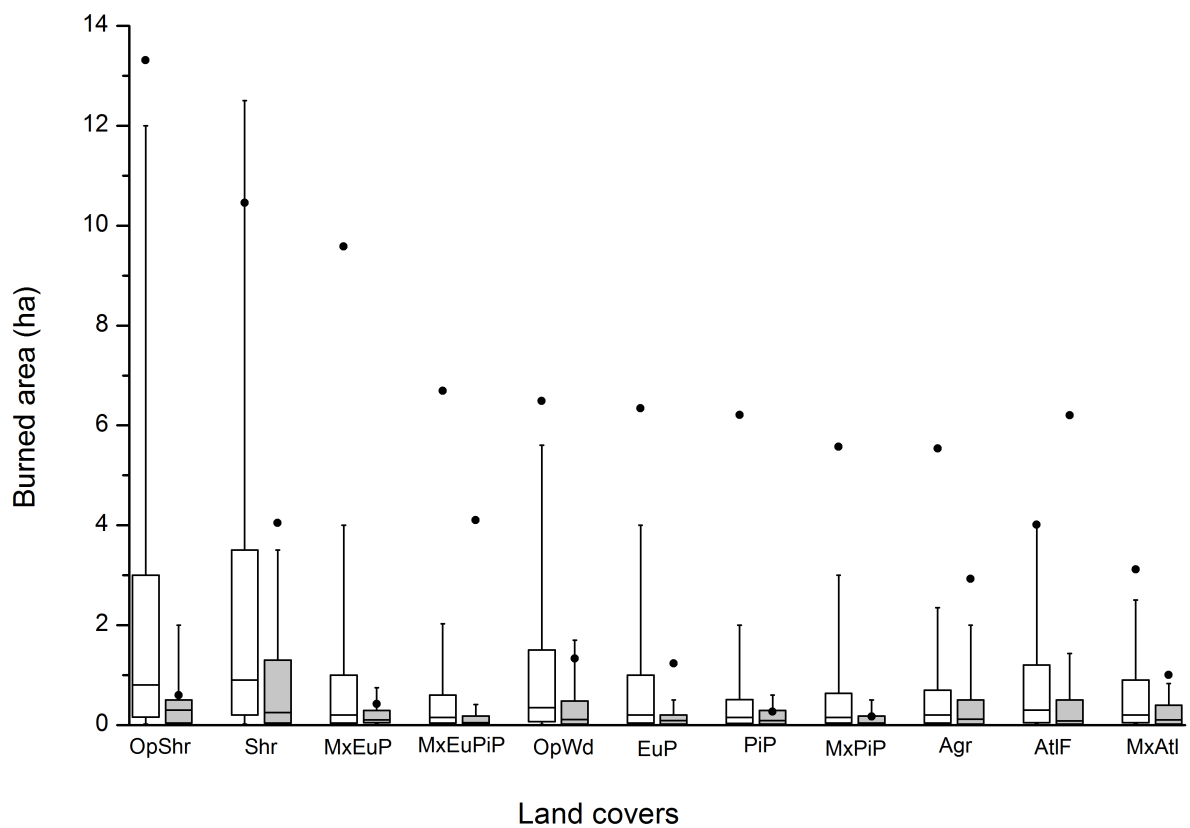
272 Table 4: Results of the analysis on the effects of fire causes, the location of ignition points  
 273 within/outside the WUI and the LULC on the size of wildfires using a Generalized Linear  
 274 Model.

Factor	d.f.	Deviance ( $\chi^2$ )	<i>P</i> value
Cause	5	96	<0.001



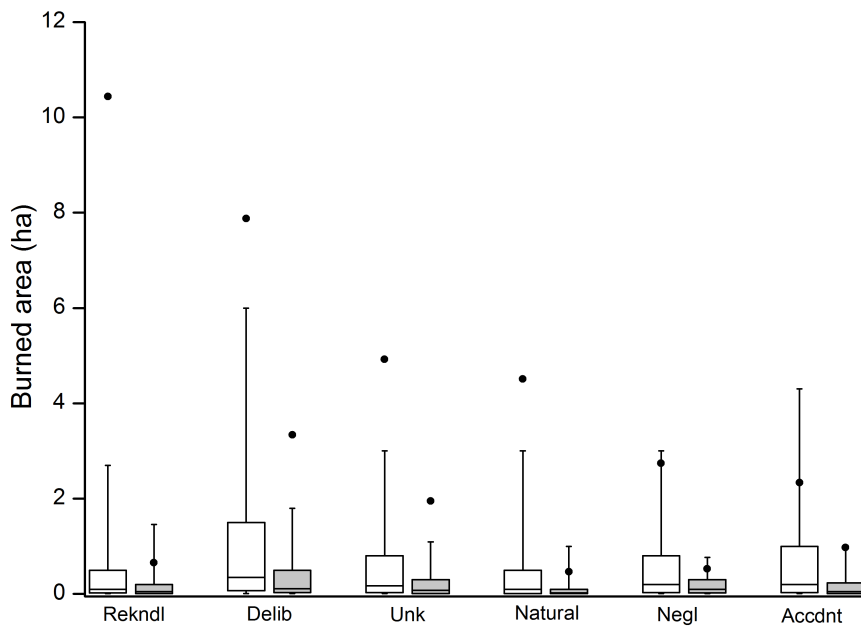
WUI	1	133	<0.001
LULC	10	459	<0.001
WUI:LULC	10	50	<0.001
Cause:LULC	50	71	0.027
Cause:WUI:LULC	105	134	0.0296

275



276

277 Fig. 2: Total area burned in fires ignited in different LULCs in non WUI (white boxes) and  
 278 WUI (grey boxes) areas. Means are represented with filled circles; boxes extend from the 25<sup>th</sup>  
 279 and 75<sup>th</sup> percentiles, with medians in the inner horizontal line, and whiskers show the 10<sup>th</sup> and  
 280 90<sup>th</sup> percentiles. Land covers are arranged according to mean fires sizes for pooled data (WUI  
 281 and non WUI), in descending order.

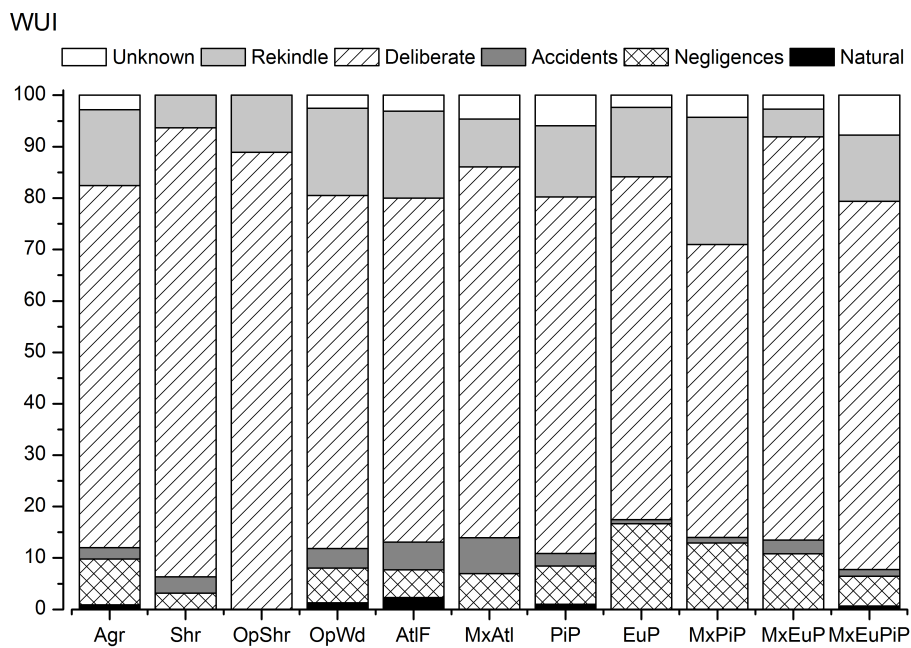


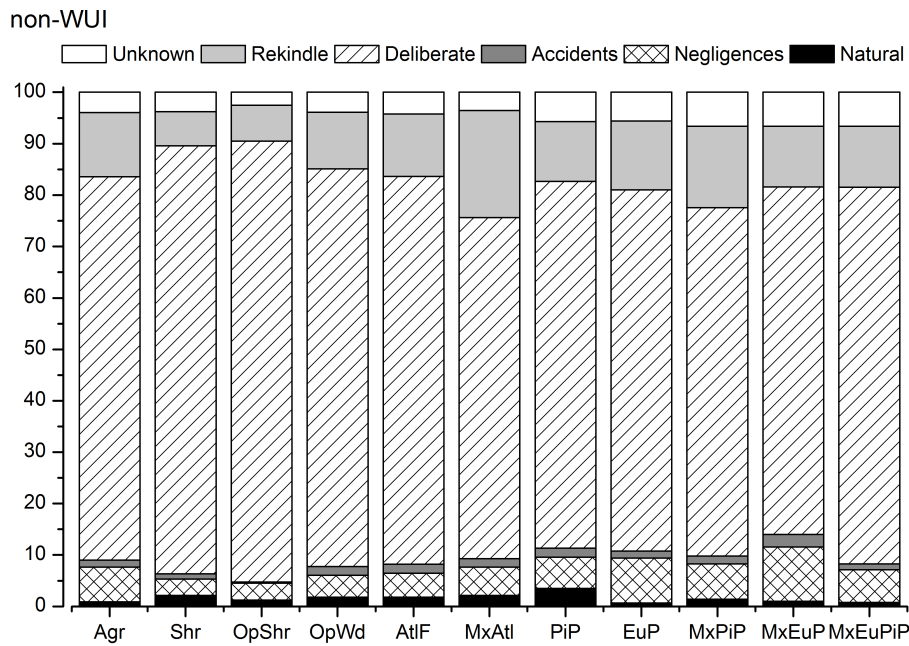
282

283 Fig. 3: Total area burned in fires with different causes in non WUI (white boxes) and WUI

284 areas (grey boxes). Means and percentiles are represented as in Fig. 2. Causes are arranged

285 according to mean fires sizes for pooled data (WUI and non WUI), in descending order.





287  
 288 Fig. 4: Percentage of fires with different causes in each LULC type in WUI and non-WUI  
 289 areas.

290 **4. Discussion**

291 **4.1. The risk of ignition**

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

297 Increased ignition risk in WUIs is the result of the proximity of human settlements that  
 298 affects the type of activities in the surrounding landscape (Bar-Massada et al 2014). The  
 299 remarkable differences found between WUI and non-WUI areas in the relative fire risk of  
 300 different LULCs (interaction WUI : LULC), particularly important for forestry plantations,  
 301 have important implications for management. Although the great majority of fires have human  
 302 related causes in the study region, the intrinsic characteristics of vegetation related to its  
 303 flammability should be also considered as important determinants of fire risk, since

304 flammability determines the consequence of the accident, negligence or even the success of a  
305 deliberate attempt to set a fire. Forestry plantations (especially those with pines), shrublands  
306 and open woodlands showed the highest ignition risk in WUI, which may be explained by the  
307 high flammability of these land covers, which results in a disproportionate increase of the risk  
308 of ignition when the density of human population and, consequently, the intensity of use  
309 increases. Pines and eucalypts, the trees most frequently used by the forestry industry (mostly  
310 *P. pinaster* and *E. globulus*), have some characteristics that increase their flammability: e.g.,  
311 high content in flammable volatile essential oils, high leaf surface area-to-volume ratio, which  
312 facilitates water loss and heat absorption, or high light penetration of their canopies, which  
313 allows more heat reaching the ground and increases moisture loss (Dimitrakopoulos and  
314 Papaioannou 2001; Schwilk and Ackerly 2001). The risk of ignition in forestry plantations  
315 decreased moderately outside the WUI, where human density is lower, although this trend was  
316 less marked in mixed plantations with pines or with pines and eucalypts.

317         However, in shrublands, where fire causes are more related with management activities,  
318 especially in relation to ranching outside the WUI (e.g. pastoral burnings; results not shown),  
319 the proximity to human settlements had less influence on ignition risk, that remained high  
320 outside the WUI. Shrublands are used for extensive livestock grazing and deliberate periodical  
321 burnings have been traditionally practiced to provide a flush of new growth more nutritious for  
322 grazers (Webb 1998), which contributes to the high percentage of deliberate fires in this land  
323 cover (the highest among all LULCs). The high fire-proneness of shrublands has been also  
324 shown in previous studies (see e.g. Nunes et al 2005; González and Pukkala 2007; Moreira et  
325 al 2009; Wittenberg and Malkinson 2009; Marques et al 2011; Oliveira et al 2013; Barros and  
326 Pereira 2014; Pereira et al 2014). This has been attributed to large amounts of fuel, close to the  
327 ground and of highly flammable species (such as *Ulex spp.*, or *Erica spp.*, Baeza et al 2002).  
328 The high flammability and fast regeneration capabilities after fire of shrublands may lead to  
329 positive feedbacks, which favour shrubland expansion and the incidence of fire (e.g., Paritsis et

330 al 2015). Positive feedbacks have also been related to Acacia woods (Mandle et al 2011),  
331 which showed very high ignition risk and are recognized as highly invasive in this region (e.g.,  
332 González-Muñoz et al 2012; Touza et al 2014). A positive relationship between their spread  
333 and fire incidence has been reported, i.e., areas currently occupied by acacias have often been  
334 previously affected by fire (Hernández et al 2014).

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

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

#### 352 **4.2. The risk of fire spread**

353 There was also a clear effect of the WUI on the risk of fire spread (lower risk of spread in  
354 WUIs, consistently with Spyrtatos et al 2007 and Lampin-Maillet et al 2011). Even though

355 there were significant interactions between the effect of the WUI and those of LULCs and fire  
356 causes, the general trend of lower risk of spread in WUIs applied to all LULCs and causes.

357         The smaller risk of spread in the WUI contrasts with the higher risk of ignition in these  
358 areas. The higher population density within the WUI favours earlier fire detection which,  
359 together with a better accessibility of these areas for fire-fighting brigades, translates into a  
360 quicker response within WUIs. In addition, WUIs are of greater priority for firefighters for the  
361 important economic and social consequences that a large fire may cause in WUIs (Moreira et al  
362 2009; Barros and Pereira 2014). Thus, earlier detection, more intense suppression efforts as  
363 well as a better accessibility, all contribute to reduce the size of fires within the WUI. In  
364 addition, vegetation within the WUI is more fragmented (Chas-Amil et al 2013), and fuel  
365 discontinuity contributes to limit the spread of fire (Syphard et al 2007).

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

377         The higher risk of fire spread related to deliberate fires reflects the success of arsonists  
378 in achieving the goal pursued. They usually aim to cause the greatest damage. For instance,  
379 they use fire accelerants such as gasoline, act on days with favourable conditions for fire (hot  
380 and windy days) or in late hours to make it difficult for aerial resources to combat the fire (e.g.,

381 Prestemon and Butry 2008; Prestemon et al 2012). Rekindle fires were even larger on average,  
382 for the influence on the mean of very large fires. In this case, the conditions that favour the re-  
383 start of a fire after it had been apparently controlled also favour fire spread in large areas before  
384 it can be safely controlled. In addition, rekindle fires show the largest difference in fire sizes  
385 between WUI and non-WUI areas, which points to the success of fire fighting measures in  
386 WUI and the higher priority of these areas for fire control.

### 387 **4.3. Implications for land management**

388 Fire prevention and management in Spain focuses on reducing fuel loads (MAGRAMA  
389 2012). Vegetation clearing is carried out by both public entities and private owners, who are  
390 compelled to clear natural vegetation in WUIs. This requires the continuous removal of  
391 vegetation in a battle against natural succession, which is costly and hardly sustainable in the  
392 long term. Alternatively, promotion of land covers with low fire risk should be considered as a  
393 low cost option for some areas, which would be more sustainable in the long term.

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

404 Agricultural abandonment, a pervasive trend in rural areas in Europe, has led to a  
405 significant increment in fuel accumulation in the landscape, especially in WUI areas,  
406 increasing fire risks (Moreira et al 2001). Land abandonment is predicted to continue in the

407 next decades (Verburg and Overmars 2009), despite European Union subsidies to fight against  
408 this trend (under the European Common Agricultural Policy). Abandoned croplands lead firstly  
409 to shrublands, which show high risk of fire. However, in the absence of major disturbances,  
410 succession ultimately leads to the establishment of native broadleaf forests in most areas in the  
411 study region (Izco 1987), with low fire risk and management costs. Meanwhile, especial  
412 attention to avoid fire would be required in order to overcome the shrubland stage of high fire  
413 risk.

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



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

438

439 **Acknowledgments**

440 This research was funded in part by the Spanish Ministry of Economy and Competitiveness  
441 (Grant ECO2012-39098-C06- 05). The Spanish Ministry of Agriculture, Food and  
442 Environment (MAGRAMA), and the Rural Affairs Department (Xunta de Galicia) provided  
443 the wildfire database.

444

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