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

3

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

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7 M. Calviño-Cancela (corresponding author)

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

9 Experimental Sciences Building. University Campus. 36310 Vigo, Spain;

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

11 M. L. Chas-Amil

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

13 Baixada Burgo das Nacións s/n. 15782 Santiago de Compostela, Spain;

14 [marisa.chas@usc.es](mailto:marisa.chas@usc.es)

15 E. D. García-Martínez

16 Departamento de Geografía y Ordenación del Territorio, Universidad de Zaragoza.

17 Facultad de Filosofía y Letras. Pedro Cerbuna 12, 50009, Zaragoza, Spain;

18 [edgm\\_73@yahoo.es](mailto:edgm_73@yahoo.es)

19 J. Touza

20 Environment Department, University of York.

21 Wentworth Way, Heslington, YO104AD, York, UK; [julia.touza@york.ac.uk](mailto:julia.touza@york.ac.uk)

22

23 **Abstract**

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

47

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

50

51 **Abbreviations**

52 WUI: Wildland-urban interface

53 LULC: land use/land cover

54 Agr: Agriculture areas

55 OpShr: Open shrublands

56 Shr: Shrublands

57 OpWd: Open woodlands

58 AtlF: Atlantic forests

59 PiP: Pine plantations

60 EuP: Eucalypt plantations

61 MxAtl: Mixed Atlantic forests

62 MxEuPiP: Mixed plantations of pines and eucalypts

63 MxPiP: Mixed pine plantations

64 MxEuP: Mixed eucalypt plantations

65

## 66 **1. Introduction**

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

76 The type of vegetation, as a land use/land cover (LULC) type, has been shown to  
77 be especially relevant for fire ignition risk (e.g., Bajocco and Ricotta 2008; Carmo et al.  
78 2011; Cumming 2001; Nunes et al. 2005). Vegetation types differ in fuel loads and  
79 flammability as well as on fuel continuity, as determined by the structure of vegetation  
80 (Saura-Mas et al., 2010). For instance, in NW Spain, native forests and agricultural  
81 areas have the lowest fire ignition risk, whereas shrublands and mixed forestry  
82 plantations have the highest ignition risk (Calviño-Cancela et al. 2016). Knowledge on  
83 the fire ignition risk associated to different vegetation types can inform landscape  
84 management policy decisions, which can promote vegetation types with lower fire  
85 ignition risk.

86 LULCs have been shown to interact with other factors such as the proximity of  
87 human settlements (Calviño-Cancela et al. 2016). In relation to this, wildland-urban  
88 interfaces (WUIs) have been defined as areas where urban development meet or  
89 intermingle with wildland, and this interfaces are of special concern for fire risk  
90 management since fires are usually more frequent in these areas and the danger to

91 human lives and properties can be higher there (e.g., Cohen 2000). The only study, to  
92 our knowledge, addressing this interaction between LULC and the WUI revealed that  
93 the fire ignition risk associated to different LULC does differ between WUI and non-  
94 WUI areas, with forestry plantations showing the highest increase in the likelihood of  
95 fire occurrence in WUI compared to non-WUI areas (Calviño-Cancela et al. 2016).  
96 Topography can also interact with LULC to modify fire risk, since it affects the  
97 distribution of vegetation (e.g., agriculture fields are usually located in flat, low areas,  
98 while forest and plantations usually occupy steeper areas, less suitable for agriculture)  
99 and some abiotic factors such as temperature and moisture content of fuels (e.g., in  
100 North versus South facing slopes).

101 In addition to these elements, nowadays the human factor is essential to  
102 understand the patterns of fire risk. Human activities have altered fire regimes  
103 worldwide, modifying fire frequency, intensity, and size of wildfires (Bowman et al.  
104 2011). Human-related causes, whether intentional or by accident, are the most frequent  
105 causes of fires (FAO 2007). In addition, certain human uses or activities are specifically  
106 associated to particular LULCs, being important drivers of fire risk in those LULCs.  
107 Common examples are agricultural burnings in farmlands or the periodical burnings in  
108 shrublands and grasslands to control woody encroachment and promote growth of new  
109 shoots, grasses and forbs for grazing (Ganteaume et al. 2013; Vélez 2002; Webb 1998).  
110 Similarly, socioeconomic factors, such as fragmentation of holdings, that limits the  
111 profit owners obtain from forestry products, urbanisation pressure, rural land  
112 abandonment or conflicts associated to forests' multiple uses have been shown to  
113 increase the probability of fire (e.g., Chas-Amil et al. 2015; Romero-Calcerrada et al.  
114 2010; Yang et al. 2007). Moreover, since population density, human behaviour and  
115 activities differ markedly between WUI and non-WUI areas, human-related factors are

116 expected to modify the fire ignition risk associated to LULCs and topographical  
117 features depending on their location within or outside WUIs areas. Topography can also  
118 affect the risk of fire related to human causes, since human accessibility and activities  
119 can be markedly determined by topography (e.g., high and abrupt areas are less  
120 accessible).

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

125

## 126 **2. Materials and methods**

### 127 **2.1. Study area**

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

### 140 **2.2 Data**

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

154 For each fire ignition point we determined the land use/land cover type (LULC),  
155 its topographic features (slope, elevation, and aspect) and the location inside or outside  
156 of the WUI. We determined the LULC type using information from the Fourth National  
157 Forest Inventory (IFN4, MAGRAMA 2011; see Calviño-Cancela et al. (2016) for  
158 further details). Areas with no or very scarce vegetation (e.g., water bodies, beaches, or  
159 artificial surfaces such as industrial or urban areas) were excluded, as well as the less  
160 frequent LULCs (grasslands, Mediterranean forests and Acacia woods), due to the low  
161 number of fires in WUI in these categories. WUI was defined as the area within a 50 m  
162 radius around buildings at a distance of up to 400 m from wildland vegetation (Law  
163 3/2007 of April 9, 2007, addressing the issues of wildfire prevention and suppression, as  
164 modified by Law 7/2012 of June 28, 2012 of Galician Forestry). The mapping of WUIs  
165 in Galicia was obtained from Chas-Amil et al. (2013).

166 Topographic variables were calculated using the Spatial Analyst extension to  
167 ArcGIS® 10.2.2 by ESRI to derive the slope, elevation and aspect, based on a 10 m  
168 spatial resolution digital elevation model (DEM, 1:5,000 scale), developed by SITGA  
169 (Galician Territorial Information System). The slope was defined as a percentage and  
170 elevation in meters. Aspect was defined as the compass direction that the slope faces: N  
171 (315° to 360° and 0° to 45°), E (45° to 135°), S (135° to 225°) or W (225° to 315°)  
172 direction.

### 173 **2.3. Data analyses**

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

181 In relation to topography, we tested whether there were differences in elevation  
182 between ignition and random points, WUI/non-WUI areas and LULCs with ANOVA,  
183 with Random/Fire, WUI/non-WUI and LULCs as fixed factors and the elevation as the  
184 variate. For differences in slope, we followed the same approach but using a generalized  
185 linear model with the negative binomial distribution and logratio as the link function,  
186 because slope followed a negative binomial distribution instead of a normal distribution.  
187 To analyse the effect of the aspect (N, S, E and W, a categorical variable), we calculated  
188 the proportional differences between the number of fires recorded in each combination  
189 of topographic features x LULCs x within/outside WUI and that in the random set,  
190 which corresponds to the expected number according to a random probability. This is

191 equivalent to selection indexes used in other studies (e.g., Moreira et al. 2001; Bajocco  
192 and Ricotta 2008), since proportional differences are the observed minus the expected  
193 frequencies divided by the expected frequencies. We performed an ANOVA with  
194 LULC and within/outside WUI as fixed factors and the proportional differences  
195 between the fire and random sets in each compass aspect (N, S, E and W) as variates.

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

214

215 **3. Results**

### 216 3.1. Topography

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

236 There was a clear contrast between WUI and non-WUI areas in the risk of fire  
237 ignition associated with aspect (Table 4; Fig. 4). Outside the WUI, the percentage of  
238 fires occurring in sites facing North was lower than expected by random chance,  
239 especially in Atlantic forests (AtlF and MxAtl; Fig. 4). In contrast, southern aspects

240 showed the opposite pattern, especially in open shrublands (Fig. 4). Within the WUI,  
241 however, there was not a clear pattern in regard to aspect (Fig. 4).

### 242 **3.2. Fire causes**

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

264 agricultural and vegetation management (Table 6). Recreation was mainly related to  
265 Mixed Atlantic forests, particularly in the WUI.

266

## 267 **4. Discussion**

### 268 **4.1. Topography**

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

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

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

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

#### 313 **4.2. Fire causes**

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

322 The distribution of LULCs in the causes space, as depicted in the ordination  
323 (Fig. 5), was very intuitive, with LULCs that seem *a priori* similar (for instance in terms  
324 of habitat structure, species composition or uses) appearing close, for the accompanying  
325 similarity in the causes of their fires. This is very revealing of the close relationship  
326 between causes and LULCs. For instance, all forestry plantations appeared clustered,  
327 especially outside the WUI, and at a certain distance from native forests (AtlF), which  
328 are very similar in structure. Note the higher incidence in forestry plantations of  
329 deliberately caused fires related to violent or mentally ill people. The economic value of  
330 these plantations may make them the target for individuals willing to cause damage to  
331 land owners. However, most fires in this category (68.6%) were assigned to  
332 pyromaniacs, which are supposed to have no conscious motivation to set fires. But the  
333 incidence of fires related to this mental disorder are often overestimated, due to the poor  
334 understanding of this condition by fire reporters and officials (Doley 2003 and  
335 references therein), which may be hiding the true conscious motivations of arsonists.  
336 AtlF appeared relatively close to agriculture (Agr), with open woodlands (OpWd)  
337 occupying intermediate positions. AtlF are expanding in some areas as a result of  
338 natural regeneration after land abandonment by farmers in rural areas (Calvo-Iglesias et

339 al. 2009, Corbelle-Rico et al. 2012). Thus, their proximity to active agricultural areas  
340 may explain their similarity in fire causes. This would also explain the intermediate  
341 position of OpWd, which are often transitional stages of colonization of abandoned  
342 fields towards forests or mixed formations (Calvo-Iglesias et al. 2009; Escribano-Avila  
343 et al. 2014). The relatively high incidence of fires related to ranching in shrublands,  
344 especially outside the WUI, is probably related to their use for extensive livestock  
345 grazing, since deliberate periodical burnings have been traditionally practiced in these  
346 areas to provide a flush of new growth more nutritious for grazers (Webb 1998).  
347 Shrublands are also especially important for hunting in Galicia, where hunting is  
348 centred on small game and particularly on rabbits (*Oryctolagus cuniculus*), which are  
349 most abundant in this type of habitat (Gálvez-Bravo 2011, Tapia et al. 2014).

#### 350 **4.3. Implications for management**

351 Our results highlight the importance of considering the interactions between  
352 factors known to influence fire ignition risk, such as the WUI, LULCs and topography.  
353 The pattern of interactions found depicts a complex scenario in relation to fire ignition  
354 risk and prompts to the importance of taking this complexity into account in order to  
355 adjust fire management measures for improved effectiveness. A better understanding of  
356 the fire ignition risk associated with different landscape features, such as vegetation,  
357 topography and proximity to urban areas, together with the underlying human-causes of  
358 fire ignitions increases the efficiency in the allocation of fire prevention measures such  
359 as surveillance or vegetation management, and facilitates the devising of regulations or  
360 education campaigns focused on increasing citizen awareness on the fire hazards related  
361 to particular activities or behaviours in certain environments (e.g. vegetation  
362 management practices in agricultural land and native vegetation, and arsonists in  
363 forestry plantations). As commented previously, knowledge on the effect of vegetation

364 on the risk of fire is especially interesting for fire prevention since vegetation can be  
365 subject to active management. Our results show that other factors such as topography  
366 and location within or outside the WUI, and differences in fire causes may affect the fire  
367 proneness of vegetation types. Certain vegetation types show more fire resistance in  
368 certain contexts (e.g. Atlantic forests in northern slopes in non-WUI areas), so that they  
369 can be used, or be promoted, to reduce fire hazard at the landscape scale. On the other  
370 hand, land covers that are particularly fire-prone in certain circumstances (e.g. open  
371 shrublands in Southern slopes outside the WUI or in higher altitudes in the WUI),  
372 require increased efforts in preventing wildfire occurrence.

373

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378

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499 Table 1: Fire causes categories used in this study.

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

500  
501

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

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

504

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

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

508

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

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

513

514

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

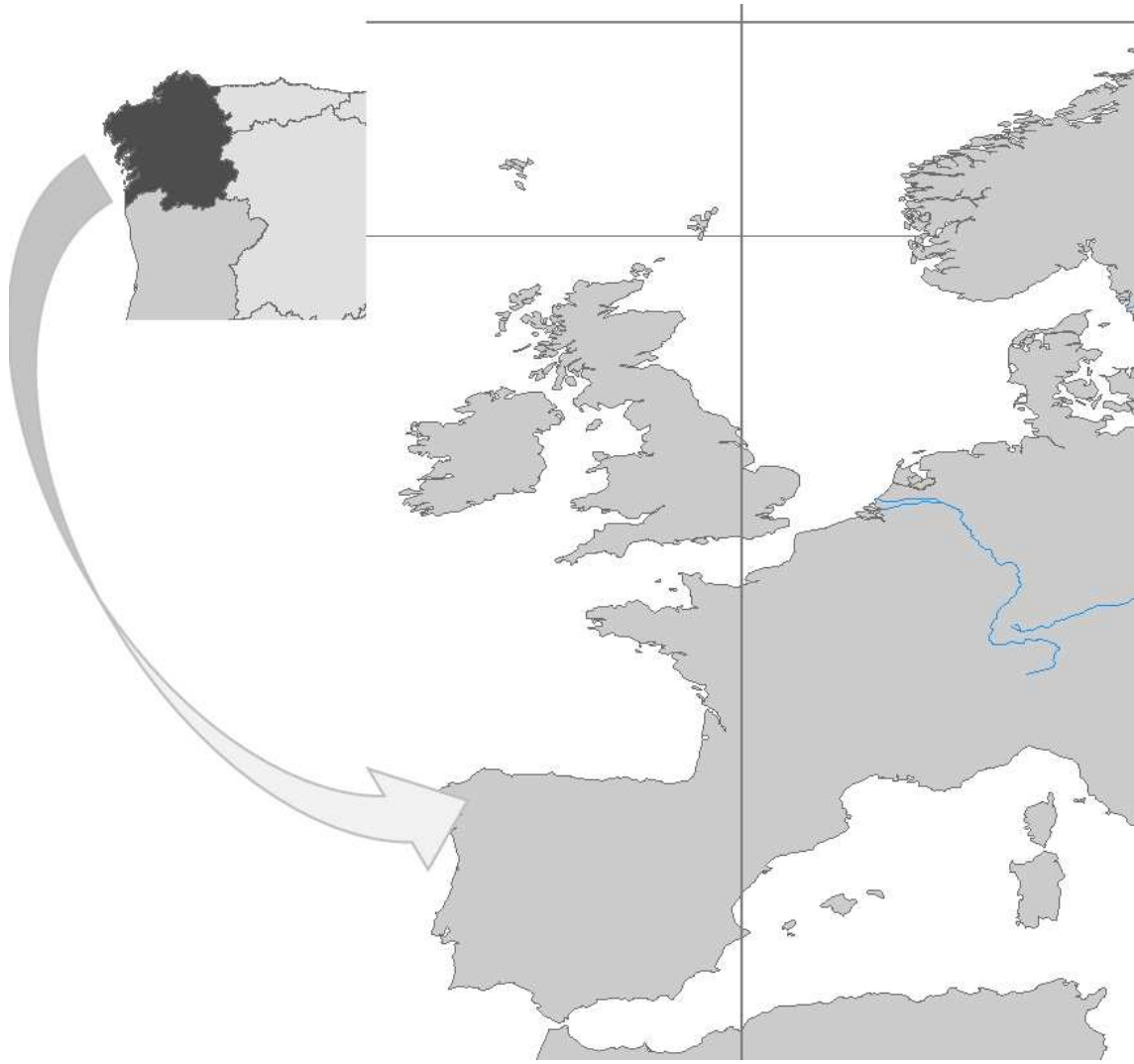
Source of variation	d.f.	SS	PseudoF	P value
WUI	1	58370	771.1	0.001
LULC	9	$3.81 \cdot 10^5$	559.2	0.001
WUI: LULC	9	$1.50 \cdot 10^5$	219.4	0.001
Residual	1980	$1.50 \cdot 10^5$		
Total	1999	$7.39 \cdot 10^5$		

517

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

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

521

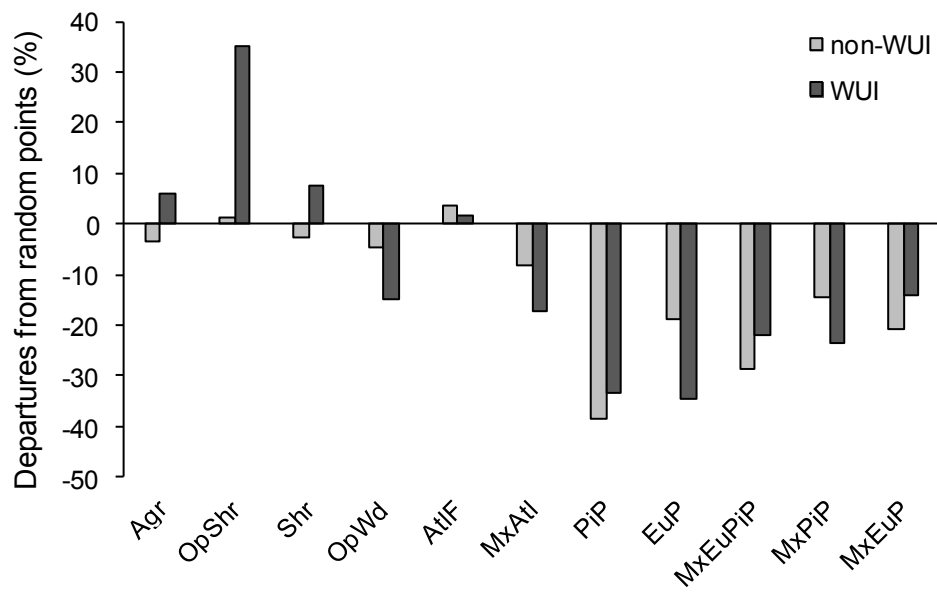


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523 Figure 1: Study area location map.

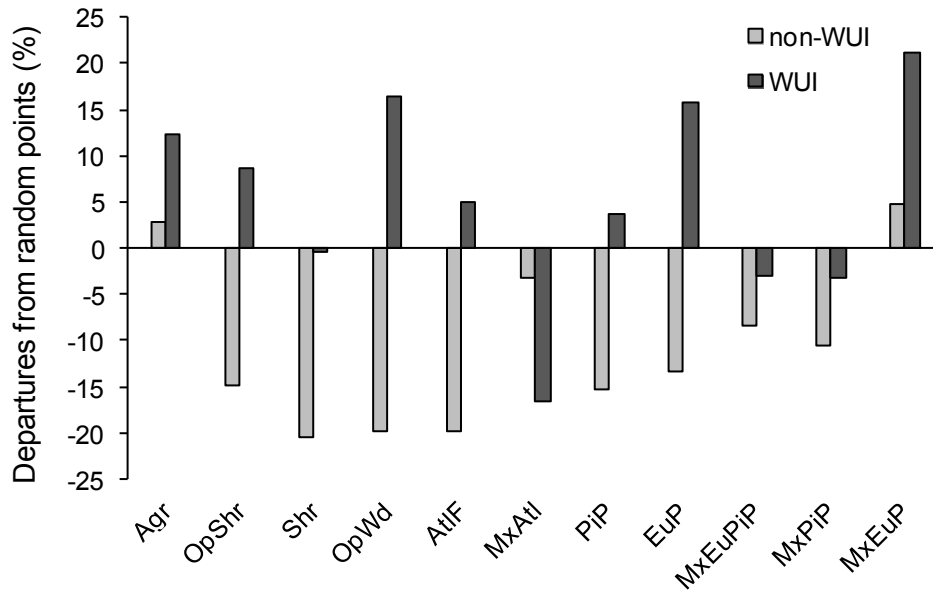
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527 Fig. 2: Differences in elevation (in percentage) between ignition and random points in  
528 the LULC types, outside the WUI (light grey) and within the WUI (dark grey).

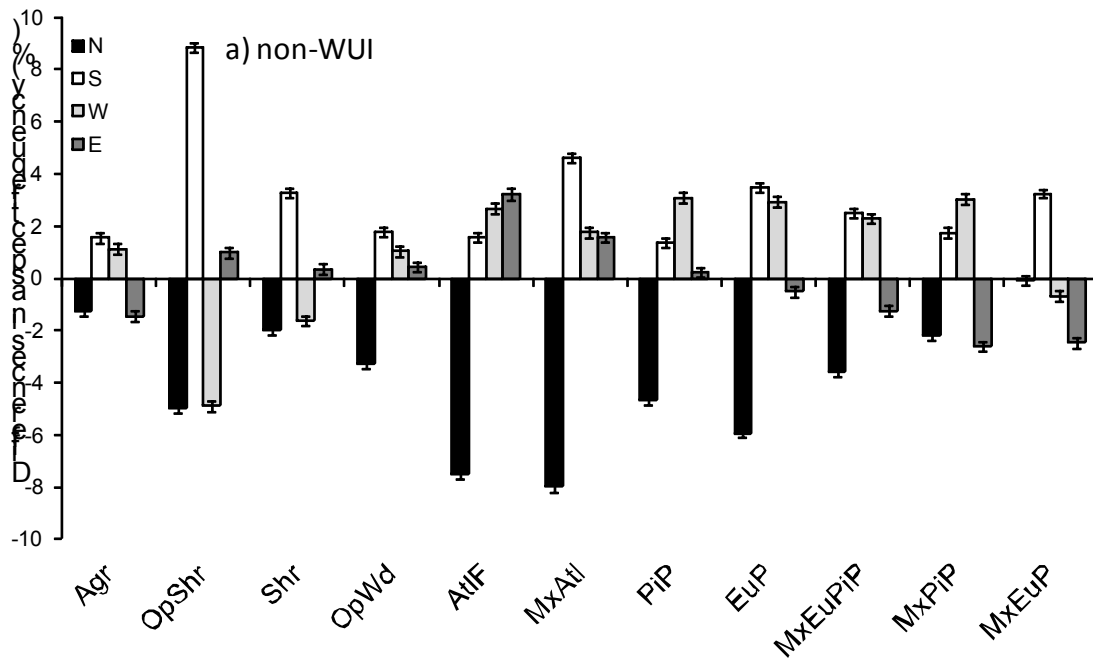


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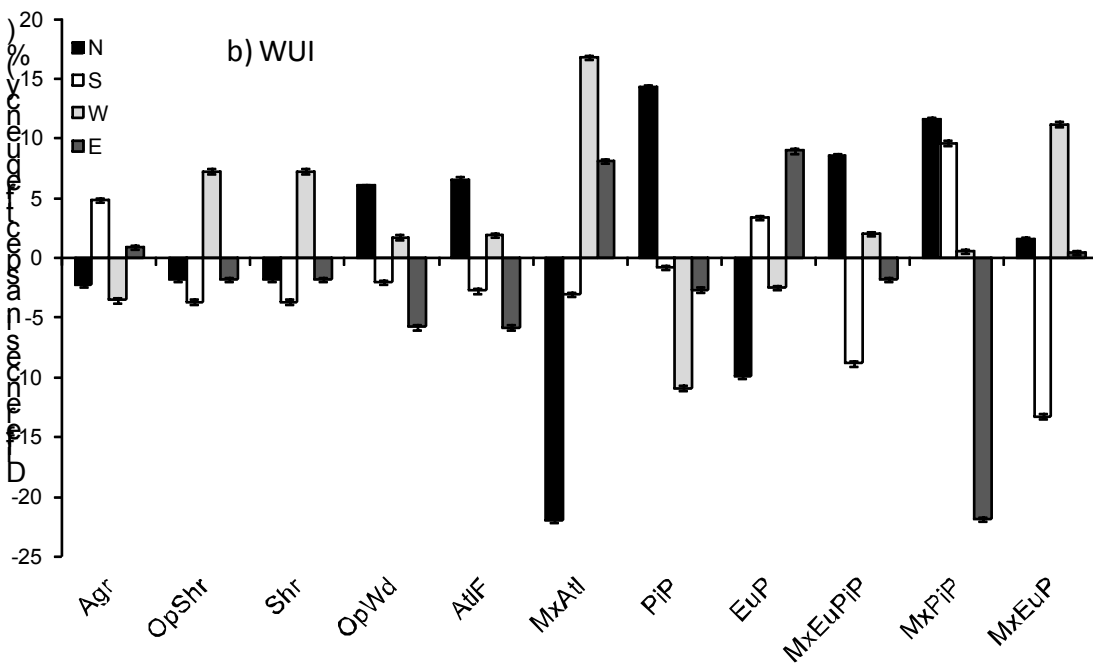
530 Fig. 3: Differences in slope (in percentage) between ignition and random points in the  
 531 LULC types, outside the WUI (light grey) and within the WUI (dark grey).

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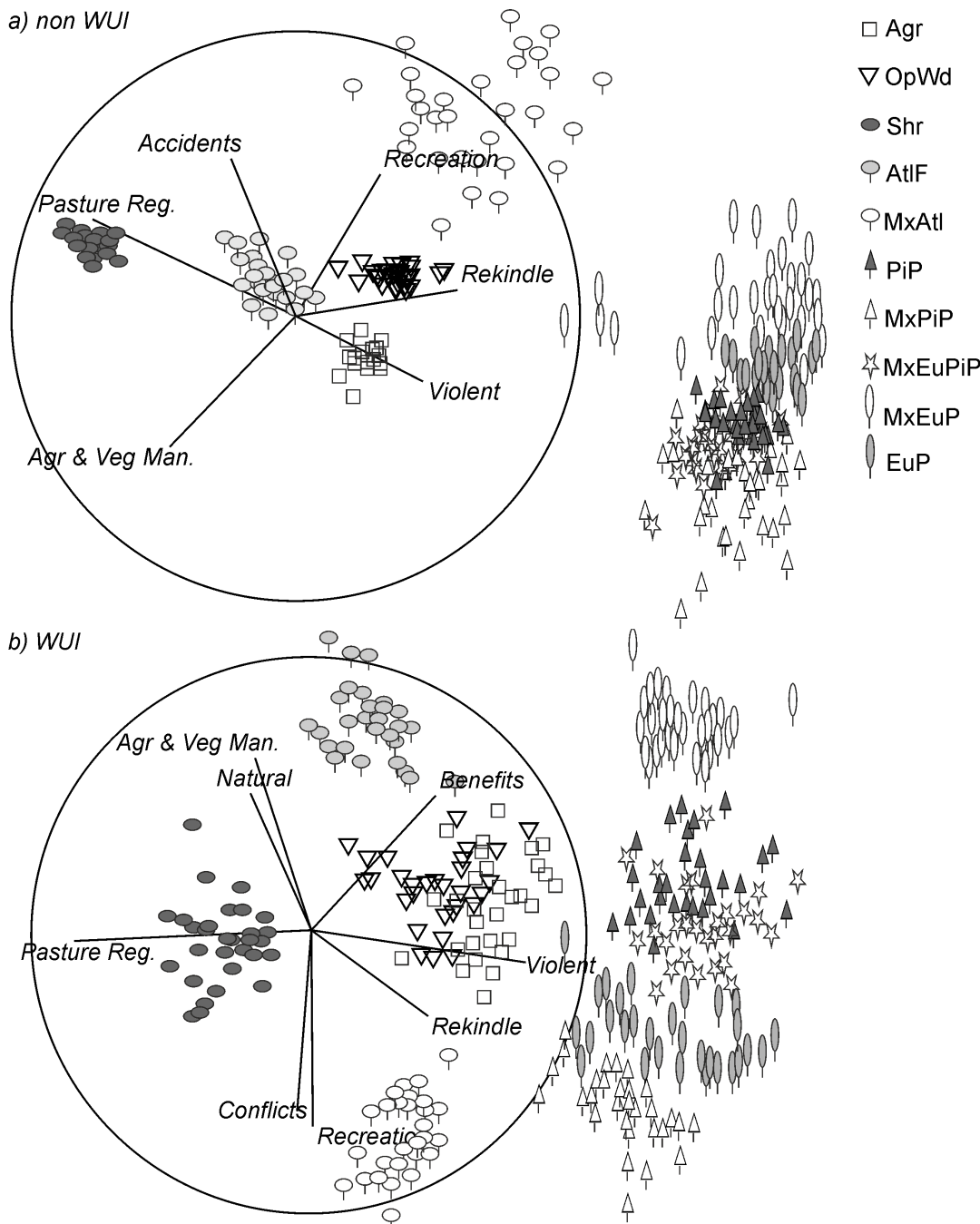


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537 Fig. 4: Fire risk depending on site aspect in non-WUI (a) and WUI areas (b). Departures  
538 from 0 show percentage increases or decreases in fire risk compared to that expected by  
539 random in each aspect (N, S, W, E) for each LULCs.

540



541

542

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

548