1 **Interacting effects of topography, vegetation, human activities and**

2 **wildland-urban interfaces on wildfire ignition risk**

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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.

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48 **Keywords:** wildfire ignition risk, Galicia, forest fires, human-related causes,

49 topography, Spain, WUI

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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

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1. Introduction

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

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

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

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.

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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**

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141   A database of 26,838 wildfire reports for the period January 1st, 2006 to

142   December 31st, 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   (315º to 360º and 0º to 45º), E (45º to 135º), S (135º to 225º) or W (225º to 315º)

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.

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215   **3. Results**

3.1. Topography

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

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

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

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264 agricultural and vegetation management (Table 6). Recreation was mainly related to

265 Mixed Atlantic forests, particularly in the WUI.

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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).

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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

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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 of in higher altitudes in the WUI),

372   require increased efforts in preventing wildfire occurrence.

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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 lighting.
Rekindle	Restart of fires.

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

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

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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	Pseudo$F$	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).

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

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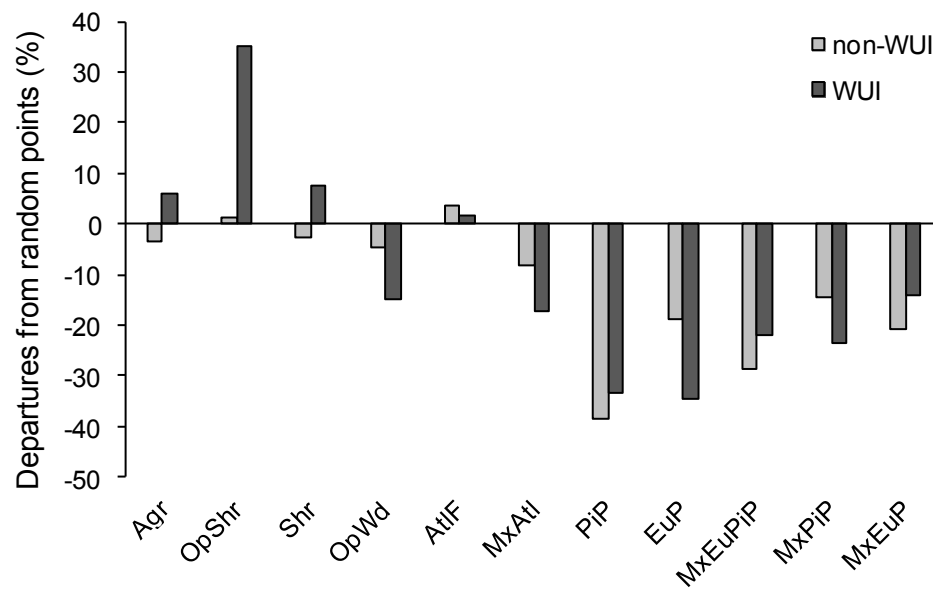
522
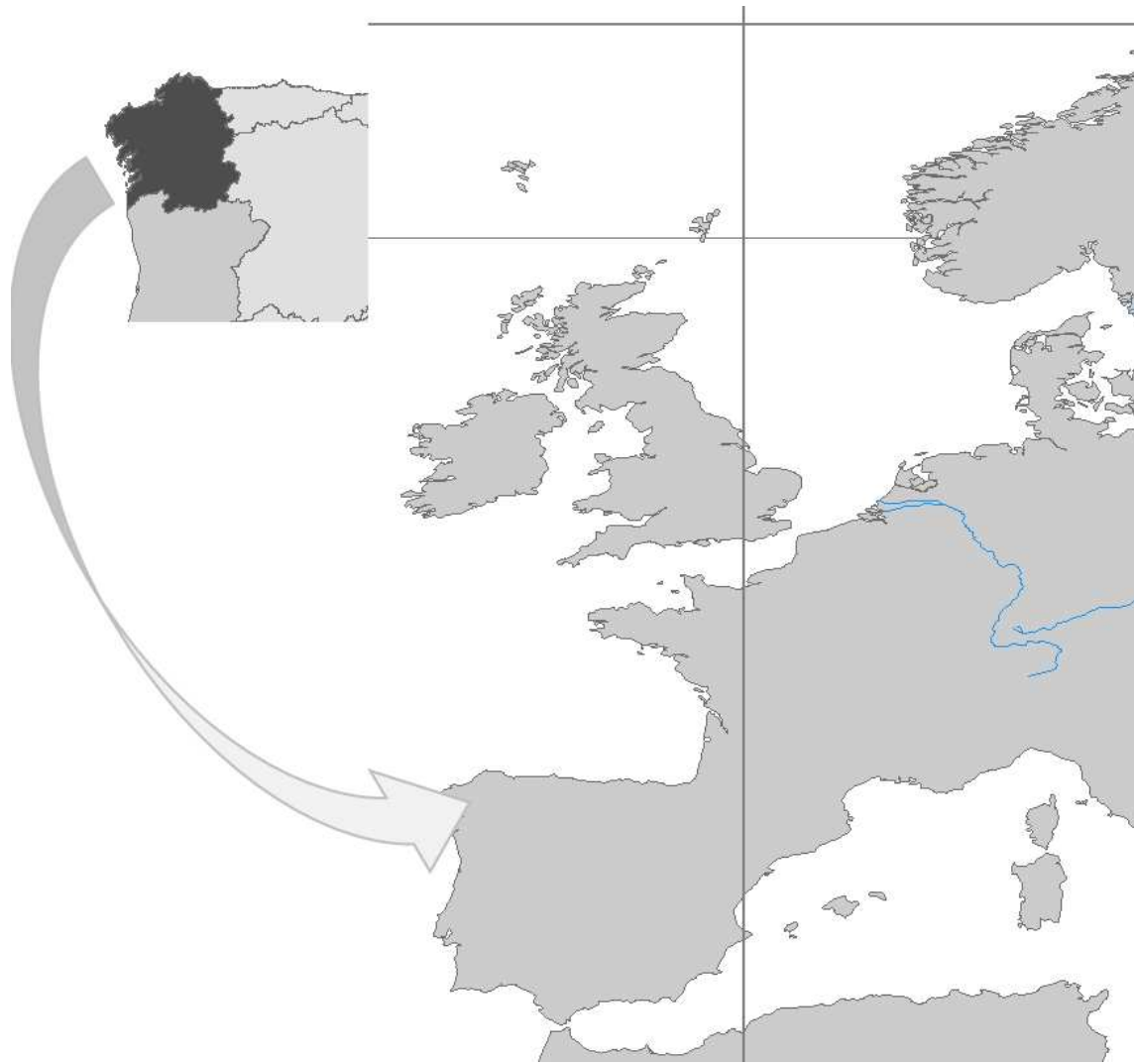
Figure 1: Study area location map.

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527 Fig. 2: Differences in elevation (in percentage) between ignition and random points in

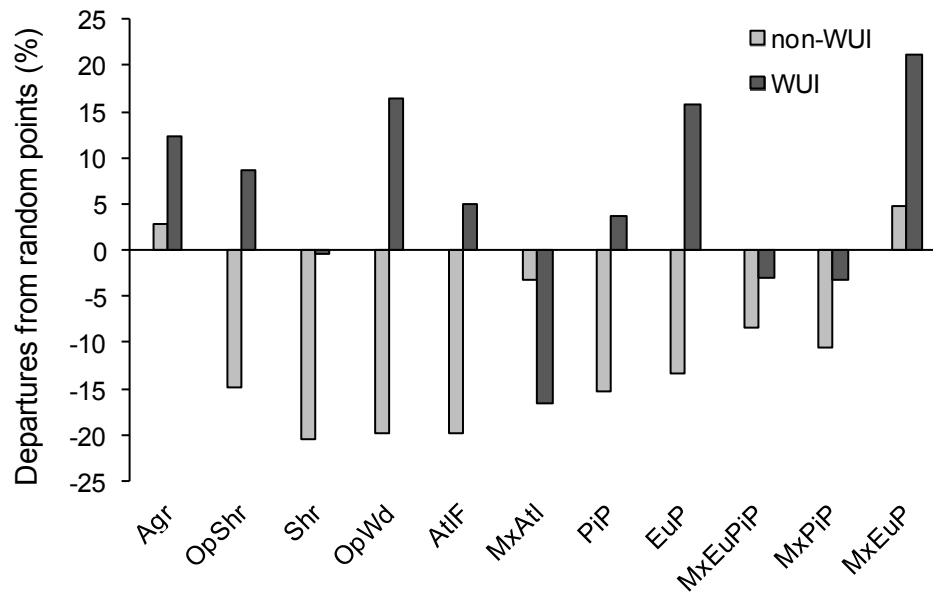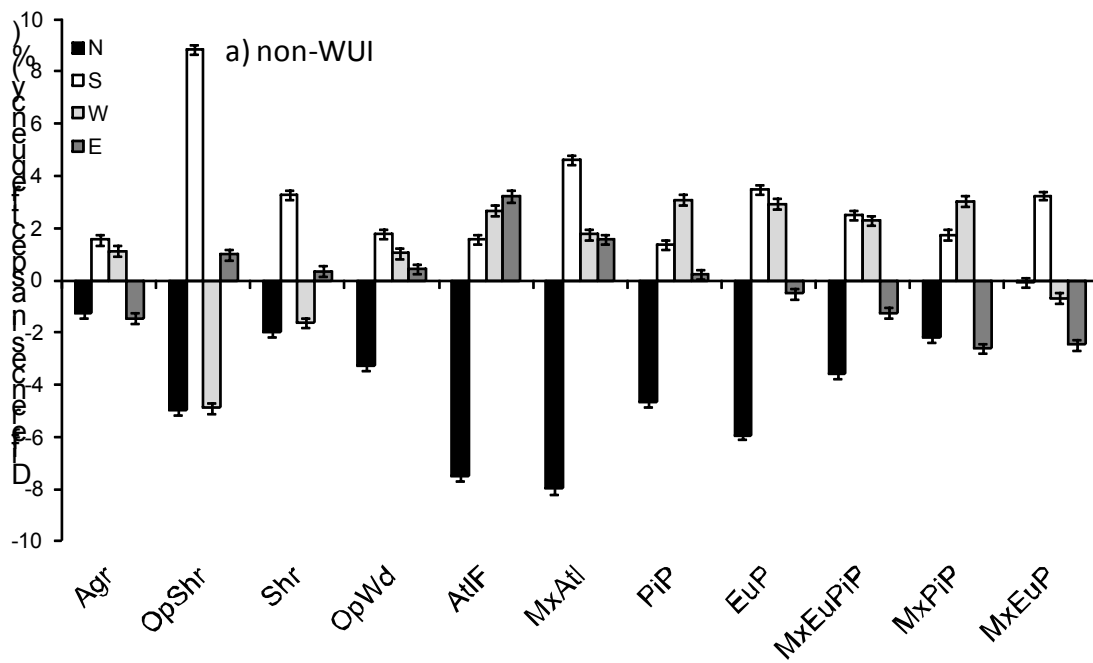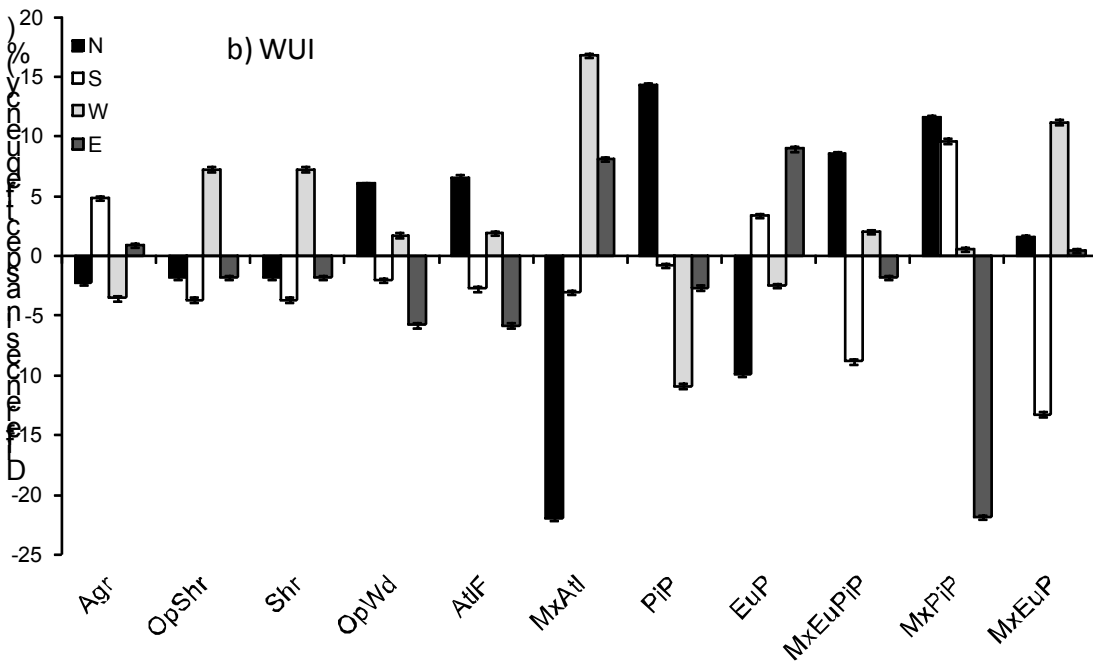528 the LULC types, outside the WUI (light grey) and within the WUI (dark grey).

529

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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Fig. 4: Fire risk depending on site aspect in non-WUI (a) and WUI areas (b). Departures

from 0 show percentage increases or decreases in fire risk compared to that expected by

random in each aspect (N, S, W, E) for each LULCs.
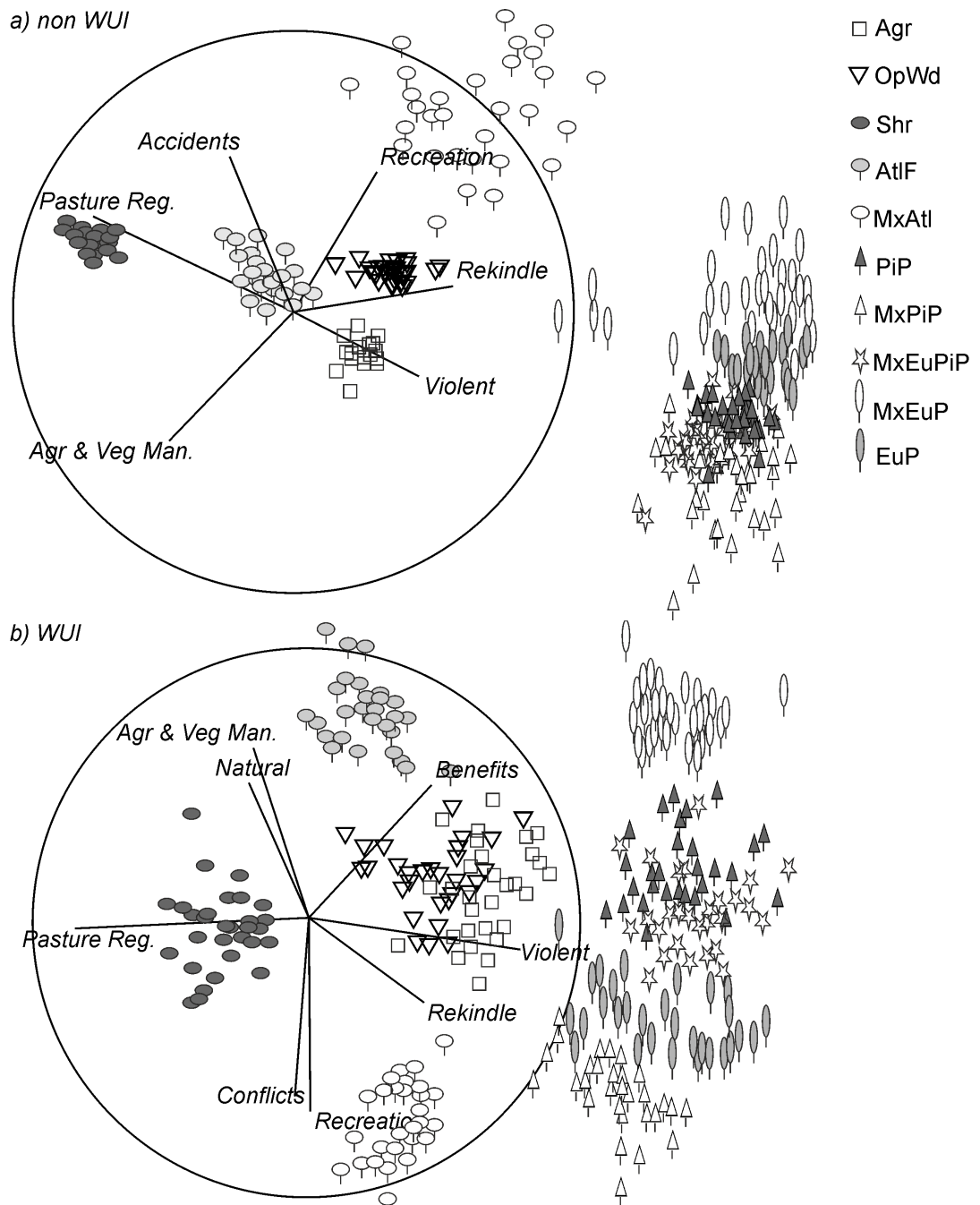
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542
543 Fig. 5: Fire causes in LULCs. NMDs ordinations of LULC types based on Bray-Curtis

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