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Land cover analysis in wildland-urban interfaces according to wildfire risk: a case study in the South of France

C. Lampin-Maillet [a], M. Long-Fournel [a], A. Ganteaume [a], M. Jappiot [a], and J.P. Ferrier [b]

[a] Cemagref, UR EMAX, 3275 route de Cezanne CS40061, 13182 Aix-en-Provence cedex 5, France

[b]Aix-Marseille I University, Emeritus Professor, Aix-En-Provence, France

Abstract

Each year, forest fires destroy about 500,000 ha of vegetation in Europe, predominantly in the Mediterranean region. Many large fires are linked to the land transformations that have taken place in the Mediterranean region in recent decades that have increased the risk of forest fires. On the one hand, agricultural fallows and orchards are slowly being colonized by vegetation, and on the other hand, the forest is not sufficiently used, both of which result in increased accumulation of fuel. In addition, urbanization combined with forest extension results in new spatial configurations called "wildland-urban interfaces" (WUI). WUI are commonly defined as "areas where urban areas meet and interact with rural lands, wildland vegetation and forests. Spatial analyses were performed using a WUI typology based on two intertwined elements, the spatial organization of homes and the structure of fuel vegetation. The organisation of the land cover in terms of representativeness, complexity or road density was evaluated for each type of WUI. Results showed that there were significant differences between the types of WUI in the study area. Three indicators (i) "fire ignition density", derived from the distribution of fire ignition points, (ii) "wildfire density", derived from the distribution of wildfire area and (iii) "burned area ratio", derived from the proportion of the burned area to the total study area were then compared with each type of WUI. Assuming that the three indicators correspond to important aspects of fire risk, we showed that, at least in the south of France, WUI are at high risk of wildfire, and that of the different types of wildland-urban interfaces, isolated and scattered WUI were the most at risk. Their main land cover characteristics, i.e. low housing and road densities but a high density of country roads, and the availability of burnable vegetation such as forested stands and shrubland (garrigue) explain the high fire risk. Improving our knowledge of relationships between WUI environments and fire risk should increase the efficiency of wildfire prevention: to this end, suitable prevention actions and communication campaigns targeting the types of WUI at the highest risk are recommended.

Keywords: Wildland-urban interface; Land cover; Spatial analysis, Wildfire risk

Introduction

In 2007, wildfires in the five most affected countries in southern Europe (Portugal, Spain, France, Italy and Greece) burned over 575,531 ha, and climate change scenarios indicate an increase in fire risk leading to increased fire frequency and extension of the fire season. Wildfires in wildland-urban interfaces (WUI) are a serious threat to communities in many countries worldwide. They can be extremely destructive, killing people and destroying homes and other structures, as was the case in California in 2003 and 2007, in Greece in 2007 and in Victoria State, Australia in 2009 (Mell et al., 2010; Haynes et al., 2010). Thus wildfires in WUI cause serious damage that has ecological, social, and economic consequences.

There are different ways to define WUI, a term now almost exclusively used in the context of wildland fire (Stewart et al., 2007). But wildland-urban interface in fact refers to an area where homes and human infrastructure meet or intermingle with wildland vegetation (Radeloff et al., 2005a; Theobald & Romme, 2007). So the term WUI actually describes the juxtaposition of housing and vegetation (Stewart et al., 2007; Lampin-Maillet et al., 2010). WUI are of great concern in terms of fire risk assessment and management (Mell et al., 2010). However, Bar Massada et al. (2009) observed that the definition of fire risk differs from study to study. The term 'fire risk' can refer to the chances of a fire starting (Hardy, 2005). For Blanchi et al. (2002), and Jappiot et al. (2009), fire risk results from the combination of (i) hazard due to the probability of ignition occurrence, and the probability of fire spreading across the landscape; (ii) and vulnerability expressed as potential damage to forests, vegetation, houses, and other buildings mainly due to the intensity of the fire. Different approaches can be used to assess wildfire risk, and recent studies showed that many indicators of wildfire occurrence (ignition), fire recurrence (frequency) and burned areas can be identified. Thus Mercer & Prestemon (2005) developed a model of the number of ignitions per district and per year (for a 10-year period) as a function of meteorological variables, population, unemployment rate, poverty rate, housing density, and the number of police officers. Sturtevant & Cleland (2007) analyzed the spatial distribution of fire occurrence as an indicator of fire ignition risk. Martinez et al. (2009) calculated the number of fires in a community divided by the surface area of the community for a specified period. The indicator was the fire ignition density calculated for entities of variable sizes. This indicator enables comparison of the number of fire ignitions in different sized areas without misjudgment (Velez, 2000 in Martinez et al., 2009). Although the fire regime accounts for many characteristics such as season, intensity, severity, Syphard et al. (2007b) limited their fire risk analysis to burned area and fire density. Mercer & Prestemon (2005) used the ratio of burned to forested area. To define wildfire density, Prestemon et al. (2002) linked the number of fires per burned area with factors such as housing density. Taking into account the results of these works, the availability of accurate data on past fires and on the main components of fire risk, three indicators able to accurately define wildfire risk were identified: ignition pressure, wildfire frequency and the extent of burned areas.

The aim of this paper is to improve knowledge of wildland-urban interfaces with respect to the ecological, topographical and socio-economic environment that determines different levels of wildfire risk. Assuming that wildfire risk is linked with the spatial configuration of the territory according to repeatable and stable relationships, we analyzed the nature of the differentiations introduced by the type of territory and its environment and their consequences for wildfire risk. Considering a WUI typology based on two intermixed elements, the spatial configuration of residential houses and the structure of burnable vegetation (Lampin-Maillet et al., 2010), we performed spatial and statistical analyses using a large number of available environmental, physical and socio-economic variables. The primary objective of the present study was to describe and characterize the human and biophysical environment of each type of WUI while emphasizing the differences between them. The secondary objective was to assess wildfire risk to structures and land cover types in WUI by determining the types of WUI most affected by wildfire risk and by characterizing the human and biophysical environment associated with different levels of risk.

Methods

Study area

Our study was conducted in a 168,000 ha area (including 59 municipalities) located in southeastern France (Limestone Provence) between the two cities, Aix-en-Provence and Marseilles (43°23’57” N, 5°22’00” E) (Fig.1). This study area is relatively homogeneous in terms of fertility (medium according to the forest site classification), elevation (less than 300 m), slope (less than 2°) and aspect. Sixty percent of the study area is dominated by forests and shrubland. There are three representative types of vegetation: pure P.halepensis stands, mixed pine-oak (pines with Q. ilex and/or Q.pubescens) stands, and shrubland (called ‘garrigue’, i.e. evergreen sclerophyllous vegetation type dominated by shrubs). These three types are representative of sequences of post-fire succession on limestone substrates in Provence. This wildland landscape alternates with agricultural land and is particularly intermingled with widespread urban settlements, roads, etc. Urban sprawl and wildland are gradually replacing agricultural fallows and consequently increasing the extent of wildland-urban interfaces. The total level of urbanization (420 inhabitants per sq km) and urban pressure are high. Community leaders in the study area are particularly concerned about the risk of wildland fire.

Landsat ETM+ scene p196r030_7k20010721, Orthorectified, USGS, Marseille, 21/07/2001.

Fig 1: Study area in southeastern France

Map of types of territory derived from the WUI map used for our spatial and statistical analyses

A WUI map was applied to the study area using the method developed in Lampin-Maillet et al. (2010). It split the territory into three: (i) four main types of wildland-urban interface based on housing configuration: isolated WUI (I), scattered WUI (S), dense clustered WUI (DC) and very dense clustered WUI (VDC); (ii) housing located outside the wildland-urban interface (O) and (iii) remaining zones (R) creating a map of types of territory (extension of the WUI map). This map had a raster format that was converted into a vector format, producing 10,487 polygons attributed to the different types of territory (I, S, DC, VDC, O, R). The territory was split into elementary spatial units described by variables related to the geographical problem (Sanders, 1989) we deal with in the present paper, wildfire risk.

Some of the polygons were too small and thus could not be used in the spatial and statistical analyses. We decided to delete them following the example of Martinez et al. (2009), who removed areas of fire occurrence in communities whose forested areas were too small and not statistically significant. In the present study, only polygons with a minimum area of 31,400 m^2 were kept. This area corresponds to the delimited area of one house located in a WUI (a WUI delimited by a 100 m radius around the house, Lampin-Maillet et al., 2010). We checked that the removed polygons whose the median surface was less than 6 m^2 were not affected by burned areas and/or fire ignition points. After this selection, 2,961 polygons were retained covering an area of 158,560 ha corresponding to around 95% of the total study area. Figure 2 is a zoom on the map of the types of territory in which each polygon represents an area of more than 31,400 m^2. Their number was large enough to allow efficient statistical analysis using Statgraphics software and spatial analysis with ArcGIS©9.2.

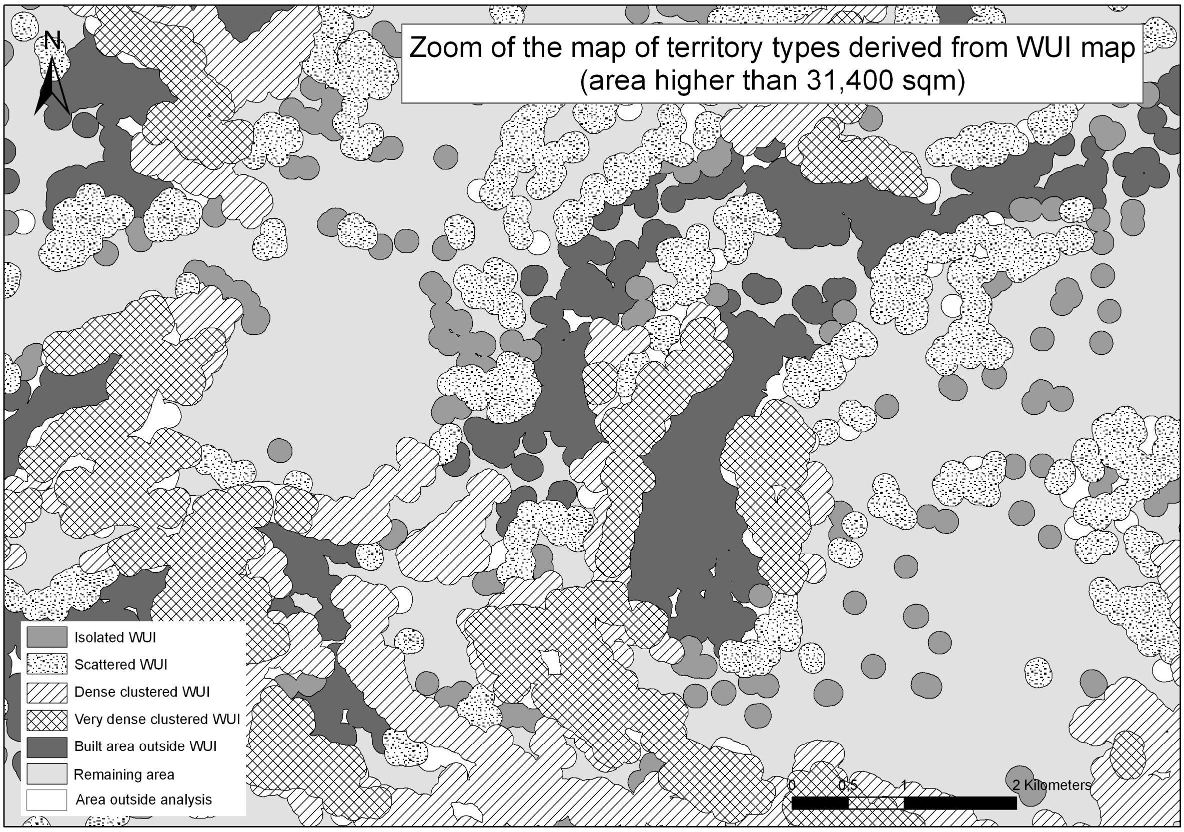

Fig 2: Zoom of the map of the territory types in the study area

Data

The nature and the origin of the dependent and explanatory variables of the analysis matrix are defined below. Their definitions are summarized in table 1.

Dependent variables

Taking into account the state of the art and data availability (available georeferenced databases on forest fires), three fire risk indicators were identified. The indicators considered as dependent variables were (i) fire ignition density (FID), (ii) wildfire density (WD) and (iii) burned area ratio (BAR) (Fig. 3). Fire ignition density was calculated as the ratio of the total number of fire ignitions in a polygon during the period 1997-2007 to the total area of the polygon. Ignition point density was chosen instead of the number of fire ignition points in order to avoid the effect of the variability of the size of each polygon. Ignition point density is expressed as the number of fire ignition points per 1,000 ha. The wildfire density was calculated as the ratio of the total number of wildfires in a polygon during the period 1990-2007 to the total area of the polygon. Like for the previous indicator, density is expressed as the number of wildfires per 1,000 ha. Finally, the burned area ratio was calculated as the ratio of the total area burned by wildfire in a polygon to the total area of the polygon expressed as a percentage of the total area of the polygon.

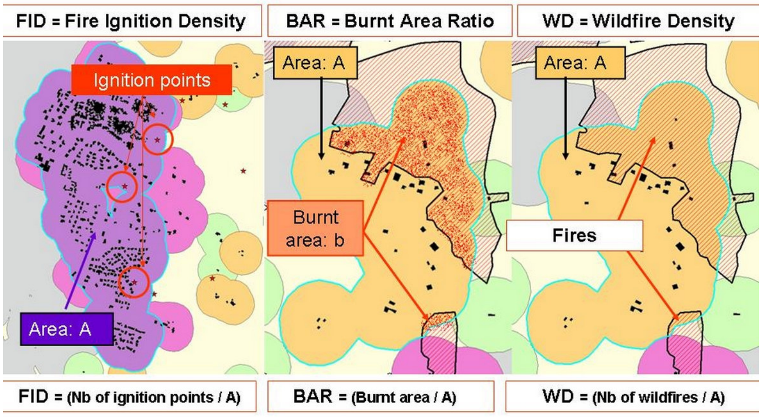

Fig 3: Definition of the explanatory variables FID, WD & BAR

Explanatory variables

Five human and six bio-physical explanatory variables were taken from available spatial databases. Among human variables, "Territory types" identified the type of territory to which each polygon belongs within six available states (isolated WUI, scattered WUI, dense clustered WUI and very dense clustered WUI, housing areas outside WUI or remaining zones). This variable took the value of 100% if the polygon belonged to the type of territory concerned, or the value of 0%, if not. "Land cover types" specified the nature of the land cover within five available states (housing, cultivated crops, forests, shrubland, sport and leisure installations). This variable was expressed as the percentage area of each type of land cover represented in the polygon. "Housing density", "Road density" and "Country road density" were calculated for each polygon from the inventory of houses, roads and country roads divided by the area of each polygon. They were expressed as the number of houses per sq km, the number of km of roads per sq km, and the number of km of country roads per sq km, respectively. Among bio-physical variables, "Slope" determined the mean slope of the polygon. It was expressed as a percentage. "Wind-Exposure" specified the decisive class of combination of exposure/wind direction for fire risk (Mariel & Jappiot, 1997) within three available states calculated taking into account the direction of the main wind, the Mistral, a north-west wind, leeward exposure (downwind), intermediate exposure to wind, and exposure to wind. It was expressed as the percentage area of each type of exposure in the polygon. "Elevation" was the median elevation of the polygon expressed in meters. "Heat - exposure" calculated from Becker's index (Becker, 1979, 1984) qualified the area as very cool, cool, neutral, hot or very hot. The variable was expressed as the percentage area of each class of exposure in the polygon. "Vegetation types" defined the type of vegetation according to five main types: hardwood, resinous, mixed hardwood-resinous, shrubland, and no vegetation. The variable was expressed as the percentage area of each type of vegetation in the polygon.

Lastly "Aggregation of vegetation" described the horizontal structure of vegetation through the aggregation index of the vegetation in three classes: no vegetation, corresponding to aggregation values equal to zero, sparse and discontinuous vegetation, corresponding to a low aggregation index, and compact and continuous vegetation, corresponding to a high aggregation index. The variable was expressed as the percentage area of each type of vegetation in the polygon.

Variables	Acronyms	Data Source	Description or range	Unit
Dependant variables				
Fire ignition density	FID	Forest National Office	Number of ignition points included in the polygon divided by the surface of the polygon, from 1997 to 2007	nb ignition/1000ha
Wildfire density	WD	DDT 13	Number of wildfires having crossed the polygon divided by the surface of the polygon, from 1990 to 2007	nb fires/1000ha
Burned area ratio	BAR	DDT13	Sum of burnt area divided by the surface of the polygon, burnt area from 1990 to 2007	%
Explanatory variables				
Human				
Territory types	I (isolated WUI), S (scaterred WUI), DC (dense clustered WUI), VDC (very dense clustered WUI), O (outside WUI), R (rest of territory)	Lampin-Maillet et *al.* 2009	Each polygon belongs to one type of territory defined through WUI mapping (0 or 100)	%
Land cover types	AGR (cultivated crops,vineyard), BOI (forests), ESN (scrubland,mattoral) URB (housing), CRE (sports ground,leisure complex, urban grassy area)	Occsol SPOT5, 2004 (2.5 m resolution)	Surface of each land cover type divided by the surface of the polygon (0 to 100)	%
House density	DB	BD topo ®IGN (polygons)	Number of houses included in the polygon divided by the surface of the polygon	houses/km^2
Road density	DR	BD topo ®IGN (lines)	Number of kilometers of roads included in the polygon divided by the surface of the polygon	road km/km^2
Country road density	DC	BD topo ®IGN (lines)	Number of kilometers of country roads included in the polygon divided by the surface of the polygon	country road km/km^2
Biophysical				
Slope	PTm (mean slope)	Derived from DEM	Mean slope of the polygon	%
Wind-Exposure	EX1 (91 to180°), EX2 (0 to 90°,181 to 270°), EX3 (271 to 360 °)	Derived from DEM	Surface of each wind-exposure type divided by the the surface of the polygon (0 to 100)	%
Elevation	ALT	DEM (50 m resolution)	Median elevation observed in the polygon	m
Heat-exposure	KR1 (very cool), KR2 (cool), KR3 (neutral), KR4 (hot), KR5 (very hot)	Becker 1979,1984	Surface of each heat-exposure type divided by the surface of the polygon (0 to 100)	%
Vegetation types	VG1 (hardwood),VG2 (coniferous), VG3 (mixed stands) VG4 (scrubland),VG0 (no vegetation)	Lampin-Maillet et *al.* 2008	Surface of each vegetation type divided by the the surface of the polygon (0 to 100)	%
Aggregation of vegetation	AI1 (no aggregation), AI2 (low aggregation), AI3 (high aggregation)	Lampin-Maillet et *al.* 2010	Surface of each aggregation level divided by the surface of the polygon (0 to 100)	%

Table 1: Variable description

Statistical analyses

The values of the variables were calculated for each polygon after various treatments were performed on the spatial georeferenced data using the software ArcGIS©9.2. Univariate analyses were performed to analyze these data on each single variable: (i) firstly in order to describe and characterize each type of territory and identify the differences among them and (ii) secondly to determine which types of WUI are most affected by fire risk and to characterize the human and biophysical environment associated with the different levels of fire risk.

Identification of characteristics describing the natural and human environment of each type of territory

The 2,961 polygons were distributed between the six types of territory in the study area (I, S, DC, VDC, O, R). Six samples were compiled, their size varying from 1,086 to 186 polygons. The median, mean, standard deviation and coefficient of variation were calculated for each variable of each sample. To test the significance of the observed differences among the six samples, the non-parametric Kruskal-Wallis test was applied because the data generally did not follow a normal distribution. In addition, box plots were drawn and the 95% confidence interval on the median was computed based on the sample median and sample standard deviation to identify which types of territory differed significantly from others. Values that did not significantly differ among themselves but did significantly differ from other values are in the same colour in Table 2. For example, for the variable AGR, there was no statistically significant difference between median values of I and S (in gray), nor was there a significant difference between median values of DC and VDC (in pink), but there was a significant difference between median values of O and R (no color), and between the two groups (I, S in grey) and (VD, VDC in pink).

Identification of characteristics describing the natural and human environment related to different levels of fire risk

The three dependant variables or indicators - fire ignition density (FID), wildfire density (WD) and burned area ratio (BAR) - were calculated for each polygon. Three analyses were performed successively to identify which type of territory was most at risk of wildfire through the indicator values and in what kind of human and bio physical environment the values of the indicator varied. The analyses consisted of a comparison between polygons with a value of the indicator greater than zero and polygons with a value of the indicator equal to zero, followed by a comparison between polygons with a low value of the indicator and polygons with a high value of the indicator. For the last comparison and for better interpretation of the results, we did not include polygons with no fires (value of the indicator equal to zero) and deleted intermediate values as done by Martinez et al. (2009) in their study on fire occurrence. Then for each indicator, each sample of polygons was classified by sorting the indicator values in ascending order and was split into three equal parts. Our analysis compared the samples of polygons with low indicator values and samples with high indicator values in order to better distinguish the conditions that lead to conditions resulting in low indicator values from those that lead to high indicator values with a sufficient number of data for relevant statistical results. The conditions of these analyses are summarized in table 3.

Indicators	Sample size with indicator value > 0	Sample size with indicator value = 0	Low values of the indicator	High values of the indicator
FID	192	2,769	Sample size : 64	
			≤ 18 fire ignition points/1,000ha	≥ 102 fire ignition points/1,000ha
WD	373	2,588	Sample size : 124	
			≤ 97 wildfires/1,000ha	≥ 227 wildfires/1,000ha
BAR	1,957	1,004	Sample size : 335	
			≤ 23 %	≥ 92 %

Table 3: Description of samples studying the positive values of FID, WD and BAR

Results

Characterization of the natural and human environment of the types of territory and particularly of the types of WUI

Table 2 lists the median, mean, standard deviation and coefficient of variation of each variable according to the type of territory. An identity card was established for each type of WUI in the study area (Figure 4) with mean values for each main variable. Half the variables within each type of WUI were not highly heterogeneous (coefficient of variation less than 100%). Some variables were distributed symmetrically with median values close to the mean.

Variables	I	S	DC	VDC	O	R	K-Wallis	Probability
Sample size	**1086**	**728**	**323**	**226**	**412**	**186**		
FID	**0** – 7,6 *(46)* 605%	**0** – 7,4 *(35)* 473%	**0** - 6 *(27)* 450%	**0** – 3,4 *(11)* 323%	**0** – 0,7 *(12)* 1714%	**0** – 2,3 *(46)* 2000%	99,1312	0.0
WD	**0** - 44 *(133)* 302%	**0** - 26 *(129)* 496%	**0** - 20 *(69)* 345%	**0** - 5 *(16)* 320%	**0** - 3 *(22)* 733%	**0** - 1 *(11)* 1100%	65,1607	1,03E-12
BAR (%)	**0** - 27 *(41)* 152%	**0** - 21 *(35)* 167%	**0** - 14 *(26)* 186%	**0** - 9 *(20)* 222%	**0** - 1 *(8)* 800%	**0** - 7 *(20)* 285%	230,46	0.0
AGR (%)	**25**-32 *(31)* 97%	**28**- 31 *(26)* 84%	**14**-18 *(18)* 100%	**11** - 13 *(11)* 85%	**64**- 56 *(33)* 59%	**21**-37 *(37)*100%	291.006	0.0
BOI (%)	**26**-33 *(31)* 94%	**25**- 30 *(25)* 83%	**31**- 33 *(24)* 73%	**18** - 20 *(14)* 70%	**0**- 5 *(8)* 160%	**11**-25 *(30)* 120%	472.93	0.0
ESN (%)	**6**-20 *(27)* 135%	**7**- 16 *(21)* 131%	**4**- 12 *(19)* 158%	**3** - 7 *(10)* 143%	**0**- 5 *(15)* 300%	**0**-6 *(28)* 467%	220.575	0.0
URB (%)	**7**-13 *(19)* 118%	**15**- 22 *(19)* 87%	**27**- 33 *(22)* 67%	**58** - 57 *(16)* 28%	**23**- 34 *(31)* 91%	**3**-0 *(33)* ND%	838.45	0.0
CRE (%)	**0**- 1 *(8)* 800%	**0**- 2 *(7)* 350%	**0**- 3 *(10)* 333%	**0** - 2 *(7)* 350%	**0**- 1 *(5)* 500%	**0**-2 *(11)* 550%	272.226	0.0
DB (houses/km^2)	**36**-41 *(27)* 66%	**79**- 94 *(57)* 61%	**115**-131*(87)*66%	**398**-394*(124)31%*	**50**-103*(143)*139%	**0**- 0 *(0)* ND%	1918.38	0.0
DC (km/km^2)	**7**- 7 *(5)* 71%	**7**- 7 *(4)* 57%	**6**- 6 *(3)* 50%	**5**- 5 *(3)* 60%	**5**- 5 *(4)* 80%	**4**- 5 *(5)* 100%	197.62	0.0
DR (km/km^2)	**1**- 3 *(5)* 167%	**4-** 5 *(5)* 100%	**6**- 8 *(6)* 75%	**11**- 12 *(4)* 33%	**5**- 7 *(7)* 100%	**2**- 4 *(5)* 125%	618.274	0.0
EX1 (%)	**7**-23 *(29)* 126%	**12**-24 *(29)* 121%	**15**-23 *(24)* 104%	**23** -26 *(23)* 88%	**6**-23 *(31)* 135%	**12**-21 *(26)* 124%	32.553	0.0000046
EX2 (%)	**52**-52 *(30)* 58%	**51**- 51 *(27)* 53%	**51**- 51 *(23)* 45%	**52**- 51 *(19)* 37%	**56**- 54 *(31)* 57%	**53**- 53 *(26)* 49%	3.92898	0.559686
EX3 (%)	**14**-25 *(30)* 120%	**15**-25 *(28)* 112%	**20**- 26 *(25)* 96%	**19** - 23 *(22)* 96%	**6**- 23 *(30)* 130%	**16**-26 *(28)* 108%	20.0342	0.0012314
PT (%)	**5**-7 *(3)* 43%	**5**-7 *(3)* 43%	**6**-8 *(3)* 38%	**6** -7 *(2)* 28%	**5**-5 *(1)* 20%	**5**-7 *(3)* 43%	357.192	0.0
ALT (m)	**206**-206*(120)*58%	**194**-192*(106)* 55%	**171**-172 *(99)* 58%	**156**-164 *(98)* 60%	**118**-122 *(97)* 80%	**182**-166*(104)* 63%	178.478	0.0
KR1 (%)	**0**-1 *(6)* 600%	**0** -1 *(6)* 600%	**0**-3 *(9)* 300%	**0** -1 *(3)* 300%	**0**-0 *(3)* ND%	**0**-2 *(7)* 350%	154.69	0.0
KR2 (%)	**0**-14 *(23)* 164%	**4** -14 *(20)* 143%	**8**-15 *(19)* 127%	**8** -12 *(14)* 117%	**0**-2 *(9)* 450%	**0**-12 *(18)* 150%	232.411	0.0
KR3 (%)	**57**-56 *(35)* 63%	**55** -56 *(32)* 57%	**50**-51 *(22)* 43%	**55** -54 *(24)* 44%	**100** -91 *(20)* 22%	**76** -67 *(32)* 48%	487.162	0.0
KR4 (%)	**8**-22 *(27)* 123%	**15** -22*(25)* 114%	**20**-24 *(23)* 96%	**23** -27 *(21)* 78%	**0**-6 *(15)* 250%	**8**-16 *(21)* 131%	299.188	0.0
KR5 (%)	**0**-6 *(16)* 267%	**0** -6 *(14)* 233%	**0**-7 *(14)* 200%	**1** -5 *(9)* 180%	**0**-1 *(3)* 300%	**0**-4 *(9)* 225%	216.828	0.0
VG0 (%)	**67**-63 *(28)* 44%	**70** -67 *(23) 34%*	**66**-64 *(22) 34%*	**76** -74 *(13)* 18%	**97**-95 *(6)* 6%	**87** -73 *(30)* 41%	666.235	0.0
VG1 (%)	**0**-2 *(5)* 250%	**0** -2 *(4)* 200%	**0**-1 *(3)* 300%	**0** -1 *(1)* 100%	**0**-0 *(1)* ND%	**0**-1 *(4)* 400%	125.076	0.0
VG2 (%)	**1**-5 *(10)* 200%	**2** -5 *(8)* 160%	**3**-8 *(11)* 137%	**3** -5 *(6)* 120%	**0**-0 *(1)* ND%	**0**-4 *(10)* 250%	540.017	0.0
VG3 (%)	**6**-15 *(20)* 133%	**7** -13 *(15)* 115%	**9**-14 *(15)* 107%	**6** -8 *(8)* 100%	**0**-1 *(2)* 200%	**3**-13 *(21)* 161%	525.281	0.0
VG4 (%)	**11**-14 *(13)* 93%	**10** -13 *(10)* 77%	**12**-14 *(8)* 57%	**12** -12 *(5)* 42%	**2**-3 *(4)* 133%	**5**-9 *(11)* 122%	596.471	0.0
AI1 (%)	**40**-42 *(32)* 76%	**41** -42 *(26)* 62%	**33** -37 *(16)* 43%	**35** -37 *(16)* 43%	**85**-81 *(17)* 21%	**69**-59 *(34)* 58%	633.589	0.0
AI2 (%)	**35**-34 *(19)* 56%	**38** -38 *(16)* 42%	**45** -44 *(14)* 32%	**50** -49 *(12)* 24%	**12**-16 *(15)* 94%	**18**-22 *(17)* 77%	707.984	0.0
AI3 (%)	**17**-23 *(21)* 91%	**15** -20 *(16)* 80%	**18** -22 *(16)* 73%	**13** -15 *(8)* 53%	**3**-3 *(3)* 100%	**7**-19 *(25)* 131%	619.823	0.0

Table 2: Median, mean (standard deviation) coefficient of variation for each variable in territory types

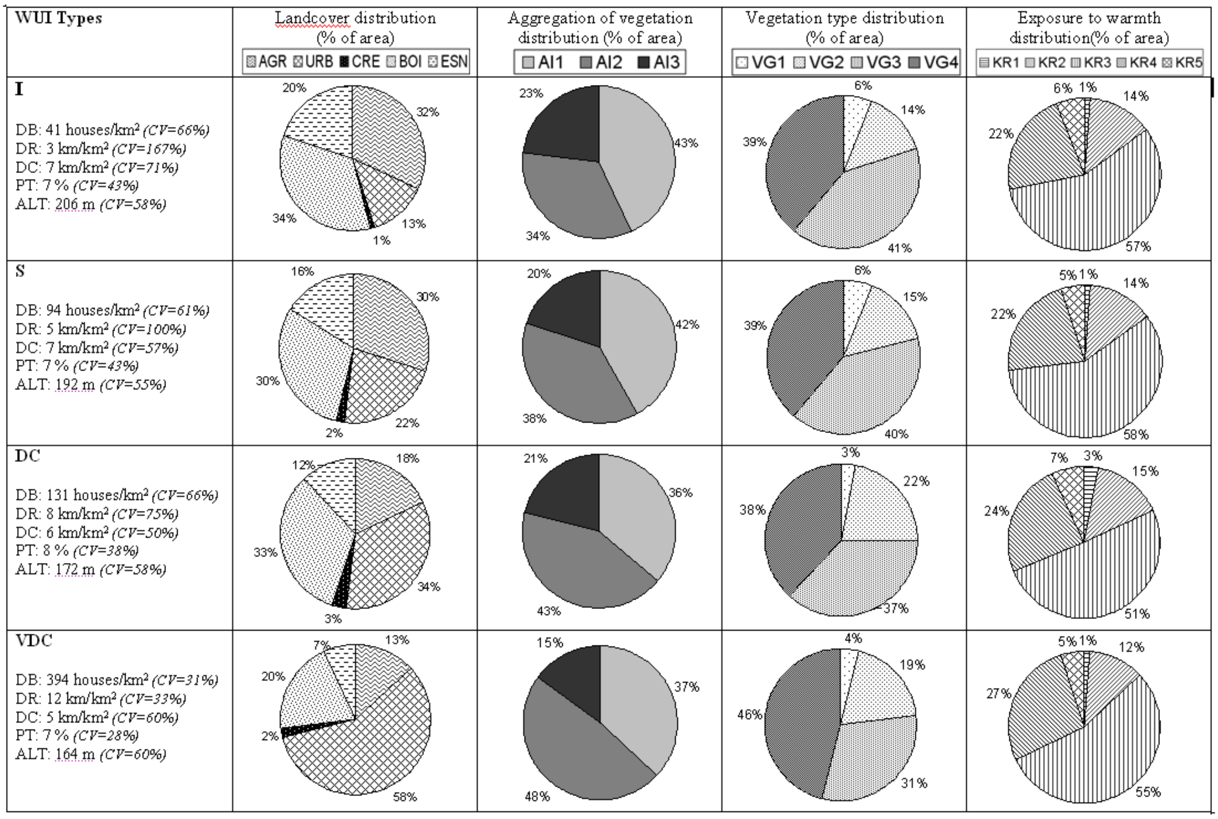

Fig 4: Identity card for WUI types

Human variables: Housing density values differed statistically according to the type of territory. Within a given type of WUI, housing density increased significantly from isolated WUI (41 houses/km^2) to very dense clustered WUI: it was 2.3 times higher in scattered WUI, 3.2 times higher in scattered dense clustered WUI and 9.6 times higher in very dense clustered WUI than in isolated WUI. Road density increased in the same way with low values in isolated WUI increasing to a value of 12 km/km^2 in very dense clustered WUI. In contrast, the density of country roads had the same high value in isolated, scattered and dense clustered WUI (around 12 km/km^2) but decreased significantly in very dense clustered WUI. Concerning the type of land cover in each type of WUI, agricultural area represented 30% of total land cover in isolated and scattered WUI, 15% in dense and very dense clustered WUI (outside WUI it reached 55%). Forested areas and other natural areas represented more than 50% in isolated WUI and around 45% in scattered and dense clustered WUI. This proportion decreased significantly in very dense clustered WUI (27%) and outside WUI (10%). Urban areas increased from 13% in isolated WUI to 22% in scattered WUI, to 34% in dense clustered, to 58% in very dense clustered WUI, and finally to 34% outside WUI. Concerning recreational areas, even though there were significant differences among the different types of WUI, the proportion of recreational areas only represented 1% to 3% of the area concerned.

Physical variables: Within and outside WUI, mean slope was generally relatively low (less than 10%) and the distribution of exposure to the Mistral wind was similar: 25% were exposed to the wind, 50% were classified as intermediate exposure and 25% were exposed leeward (downwind). The median elevation was lowest outside WUI and highest in isolated WUI. Exposure to very cool and very hot situations was rare in the study area (only 7%). The proportion of neutral exposure ranged from 51% to 56% in WUI and was predominant outside WUI. Exposure to hot situations was well represented in the different types of WUI (around 25%) but was only around 6% outside WUI.

Natural variables: The composition of the vegetation within the WUI was stable. The proportion of hardwood vegetation varied slightly from 3% to 6%. The proportion of resinous vegetation and mixed hardwood-resinous vegetation represented more than half the forested and other natural areas (50% to 59%). Shrubland (garrigue) represented 38% to 46% of the area and was predominant in very dense clustered WUI. Outside WUI, garrigue vegetation dominated (75%) and resinous and mixed vegetation represented 25% (hardwood was almost absent). The distribution of the aggregation index varied slightly within WUI with 37% to 43% for values equal to zero, 34% to 48% for low values and 15% to 23% for high values. Outside WUI, values equal to zero represented 80%.

Dependent variables:

Univariate analysis of each dependent variable (FID, WD and BAR) performed on all the polygons belonging to each type of territory produced no useful information as the heterogeneity of the distribution of the values was too high. However, the mean values of

FID, WD and BAR decreased from isolated WUI to very dense clustered WUI and finally outside WUI. Isolated and scattered WUI had the highest FID and BAR values.

Characterization of the natural and human environment with respect to the different levels of wildfire risk

For each indicator (FID, WD and BAR) figure 5 shows the distribution of polygons in the different types of territory and according to levels of risk based on the indicator values. Polygons with medium and high FID were most common in isolated and scattered WUI, while those with low FID were more frequent in clustered WUI. Polygons with high WD were most common in isolated WUI, and those with medium WD were also common in isolated and scattered WUI. Low WD values were equally frequent in scattered and clustered WUI. Finally polygons with high and medium BAR were most common in isolated and scattered WUI. Low BAR values were more common in clustered WUI.

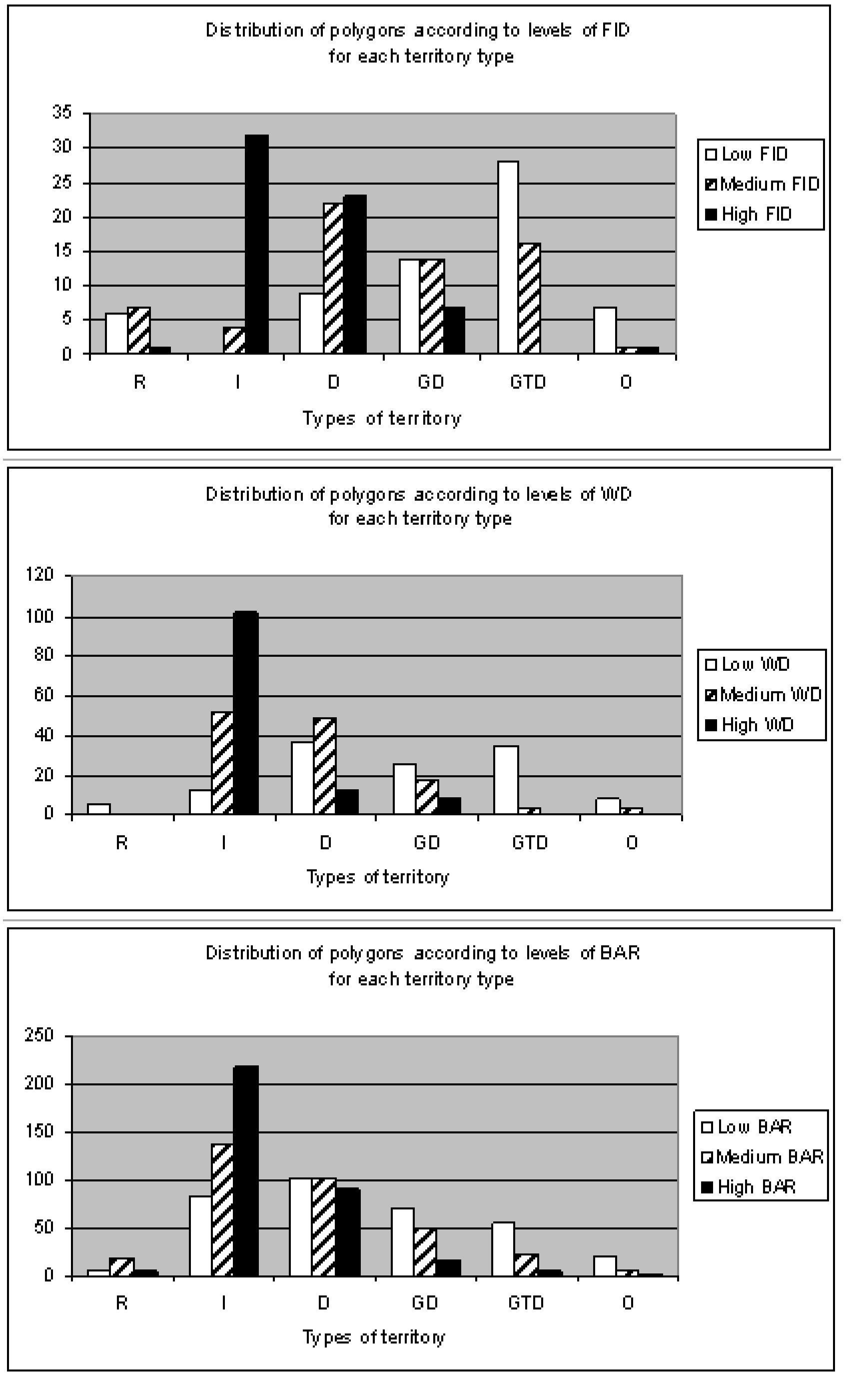

Fig 5: Distribution of polygons for each FID, WD and BAR according to risk levels

The most significant results are summarized in tables 4 to 6. The median, mean, standard deviation and coefficient of variation and values of the Kruskal-Wallis tests enabled the following comparisons (values in the following paragraph are mean values).

Variables	Polygons with FID equal to 0 (*)	Polygons with positive FID (*)	Kruskal-Wallis Test	Probability		Variables	Polygons with Low FID (*)	Polygons with High FID (*)	Kruskal-Wallis Test	Probability
	Sample size: **2769**	Sample size: **192**					Sample size: **64**	Sample size: **64**		
AGR (%)	**27** – 33 *(31)* 94%	**13** – 18 *(19)* 105%	28,5828	8,97757E-8		AGR (%)	**16** - 19 *(16)* 84%	**6** - 18 *(22)* 122%	4,73	0,0296
BOI (%)	**18**– 26 *(27)* 104%	**27** – 32 *(23)* 72%	21,1135	0,000004		BOI (%)	**25** - 26 *(16)* 62%	**33** - 35 *(27)* 77%	2,81424	0,093
ESN (%)	**2**– 15 *(23)* 153%	**9**– 18 *(22)* 122%	42,6066	6,69346E-11		ESN (%)	**5** - 9 *(10)* 111%	**21**- 28 *(27)* 96%	12,5755	0,0003
URB (%)	**14**– 24 *(25)* 104%	**24**– 30 *(23)* 77%	20,3108	0,000006		URB (%)	**53** - 44 *(23)* 52%	**10** - 15 *(16)* 107%	46,0597	1,14^{E}-11
CRE (%)	**0**– 1,6 *(8)* 500%	**0**– 2 *(10)* 500%	57,3676	0,0		CRE (%)	**1** - 1 *(2)* 200%	**0** - 3 *(14)* 467%	40,9213	1,58^{E}-10
DB (h/km^2)	**54**– 91 *(112)* 123%	**100**–178 *(185) 104%*	64,0052	0,0		DB (h/km^2)	**249** - 299 *(215)* 72%	**53** - 59 *(31)* 53%	54,7828	0,0
DC (km/km^2)	**6**– 7 *(4)* 57%	**6**– 6 *(3)* 50%	0,0168309	0,896		DC (km/km^2)	**5,5**- 5,8 *(2)* 34%	**7** – 7,3 *(4,6)* 63%	4,99598	0,025
DR (km/km^2)	**4**– 5 *(6)* 120%	**6**– 7 *(5)* 71%	42,3984	7,44509E-11		DR (km/km^2)	**9,7**- 9,3 *(4,8)* 52%	**4,8**- 6 *(6)* 100%	15,3325	0,00009
EX1 (%)	**10**– 23 *(28)* 122%	**15**– 24 *(25)* 104%	5,01257	0,025		EX1 (%)	**24**- 26 *(20)* 77%	**10**- 23 *(30)* 130%	6,33326	0,011
EX2 (%)	**52**– 52 *(28)* 54%	**52**– 50 *(21)* 42%	1,24948	0,263		EX2 (%)	**52**- 49 *(12)* 24%	**53**- 50 *(28)* 56%	0,308251	0,578
EX3 (%)	**14**– 25 *(29)* 116%	**23**– 27 *(24)* 89%	7,63091	0,005		EX3 (%)	**22**- 25 *(19)* 76%	**19**- 27 *(29)* 107%	0,993845	0,318
PT (%)	**5**–7 *(3)* 43%	**6,3**–8 *(3)* 37%	52,6359	0,0		PT (%)	**6,6**- 7,1 *(2,1)* 29%	**6,3**- 8,3 *(4)* 48%	0,539293	0,462
ALT (m)	**181**–181 *(112)* 62%	**187**–182 *(101)* 55%	0,0992271	0,752		ALT (m)	**185** - 172 *(91)* 53%	**187** - 196 *(111)* 57%	1,04986	0,305
KR1 (%)	**0**–1,4 *(6)* 428%	**0**–2 *(4)* 200%	126,802	0,0		KR1 (%)	**0,4**- 1,8 *(3)* 167%	**0**- 1,6 *(4)* 250%	15,9913	0,00006
KR2 (%)	**0**–12 *(20)* 167%	**10**–17 *(19)* 111%	42,0002	9,12647E-11		KR2 (%)	**11**- 14 *(11)* 78%	**4**- 18 *(26)* 144%	2,90382	0,088
KR3 (%)	**65**–62 *(33)* 53%	**48**–50 *(26)* 52%	28,8077	7,99347E-8		KR3 (%)	**51**- 54 *(20)* 37%	**36**- 41 *(31)* 76%	7,26395	0,007
KR4 (%)	**8**–20 *(25)* 125%	**20**–24 *(21)* 87%	23,4335	0,000001		KR4 (%)	**22**- 25 *(17)* 68%	**18**- 26 *(27)* 104%	0,952231	0,319
KR5 (%)	**0**–5 *(13)* 260%	**1**–8 *(15)* 187%	68,4247	0,0		KR5 (%)	**4**- 6 *(6)* 100%	**0**- 11 *(20)* 181%	8,81	0,002
VG0 (%)	**78**–71 *(26)* 37%	**66**–63 *(21)* 33%	32,0171	1,52822E-8		VG0 (%)	**70**- 69 *(16)* 23%	**57**- 59 *(24)* 41%	6,6716	0,009
VG1 (%)	**0,04**–1,4 *(4)* 285%	**0,1**–1,1 *(3)* 273%	11,0325	0,000894806		VG1 (%)	**0,4**- 0,8 *(1)* 125%	**0**- 1,8 *(4)* 222%	13,3011	0,0002
VG2 (%)	**0,8**–5 *(9)* 180%	**4**–8 *(10)* 125%	77,2765	0,0		VG2 (%)	**5**- 5 *(4)* 80%	**4**- 7 *(10)* 143%	0,785746	0,375
VG3 (%)	**4**–12 *(17)* 142%	**9**–14 *(14)* 100%	27,9113	1,27005E-7		VG3 (%)	**10**- 12 *(10)* 83%	**10**- 17 *(18)* 106%	0,188068	0,664
VG4 (%)	**9**–12 *(11)* 92%	**13**–15 *(8)* 53%	41,8321	9,94596E-11		VG4 (%)	**13**- 13 *(6)* 46%	**13**- 16 *(10)* 63%	1,07931	0,298
AI1 (%)	**47**–48 *(31)* 65%	**31**–34 *(22)* 65%	38,3269	5,98324E-10		AI1 (%)	**35** - 39 *(17)* 44%	**23** - 32 *(25)* 78%	4,88953	0,027
AI2 (%)	**34**–33 *(19)* 58%	**44**–43 *(14)* 33%	48,248	3,75577E-12		AI2 (%)	**44** - 42 *(12)* 108%	**43** - 43 *(16)* 37%	0,0090843	0,924
AI3 (%)	**11**–18 *(19)* 105%	**20**–23 *(16)* 70%	39,1046	4,01693E-10		AI3 (%)	**17** - 19 *(11)* 58%	**22** - 25 *(18)* 73%	3,33142	0,067

Table 4: Median, mean (standard deviation) coefficient of variation for each variable for FID values

Variables	Polygons with WD equal to 0 (*)	Polygons with positive WD (*)	Kruskal-Wallis Test	Probability			Polygons with Low WD (*)	Polygons with High WD (*)	Kruskal-Wallis Test	Probability
	Sample size:**2588**	Sample size:**373**					Sample size:**124**	Sample size:**124**		
AGR (%)	**27**– 34 *(31)* 91%	**13**– 22 *(25)* 114%	49,6091	1,87E-12		AGR (%)	**14** 21 *(22)* 105%	**2**– 18 *(25)* 139%	11,2471	0,0007
BOI (%)	**18**– 27 *(27)* 100%	**22**– 27 *(25)* 93%	1,33255	0,248		BOI (%)	**22**- 27 *(20)* 74%	**20**- 28 *(30)* 107%	1,37403	0,241
ESN (%)	**1,5**– 13 *(22)* 169%	**21**– 29 *(21)* 72%	211,579	0,0		ESN (%)	**12**- 17 *(18)* 106%	**36**- 42 *(33)* 78%	34,4261	4,427E-9
URB (%)	**14**– 25 *(26)* 104%	**12**– 20 *(22)* 110%	6,66675	0,009		URB (%)	**28**- 34 *(23)* 68%	**5**- 11 *(16)* 145%	88,4019	0,0
CRE (%)	**0**– 1,7 *(8)* 470%	**0**– 1,1 *(6)* 545%	0,110909	0,739		CRE (%)	**0**- 1 *(2)* 200%	**0**- 1 *(7)* 700%	44,6905	2,307E-11
DB (h/km^2)	**56**– 95 *(119)* 125%	**57**–108 *(134)* 124%	1,74641	0,186		DB (h/km^2)	**133**-212 *(186)* 88%	**29**- 42 *(28)* 67%	117,202	0,0

DC (km/km^2)	**6**– 6,6 *(4)* 61%	**6,7**– 7,2 *(4)* 56%	8,03502	0,004		DC (km/km^2)	**5,8**- 6 *(3)* 50%	**7,3**- 8 *(5)* 62%	10,9376	0,0009
DR (km/km^2)	**4,2**– 5,5 *(6)* 109%	**3,3**– 4,7 *(5)* 106%	7,01517	0,008		DR (km/km^2)	**6,7**- 8 *(5)* 62%	**0**- 3 *(5)* 167%	58,4752	0,0
EX1 (%)	**9**– 23 *(28)* 122%	**21**– 28 *(27)* 96%	20,5956	0,000005		EX1 (%)	**28**- 29 *(23)* 79%	**14**- 25 *(29)* 116%	5,77785	0,0162
EX2 (%)	**52**– 52 *(28)* 54%	**53**– 53 *(26)* 49%	0,55946	0,454		EX2 (%)	**51**- 51 *(20)* 39%	**60**- 59 *(30)* 51%	5,32371	0,0210
EX3 (%)	**17**– 26 *(29)* 111%	**10**– 19 *(24)* 126%	11,3349	0,0007		EX3 (%)	**13**- 20 *(20)* 100%	**0**- 16 *(25)* 156%	13,6738	0,0002
PTm (%)	**5** – 6,6 *(3)* 45%	**6**– 8 *(4)* 50%	75,9149	0,0		PTm (%)	**7** - 8 *(3)* 37%	**6**- 8 *(4)* 50%	3,1683	0,075
ALT (m)	**187**–183 *(114)* 62%	**153** – 168 *(94)* 56%	6,35584	0,011		ALT (m)	**156** - 158 *(84)* 53%	**159**-188 *(103)* 55%	3,80298	0,051
KR1 (%)	**0** – 1,4 *(6)* 428%	**0** – 1,7 *(6)* 353%	12,3115	0,0004		KR1 (%)	**0** - 2 *(5)* 250%	**0**- 1 *(7)* 700%	33,8764	5,872E-9
KR2 (%)	**0** – 12 *(20)* 167%	**3** – 11 *(16)* 145%	0,375909	0,5398		KR2 (%)	**7** - 11 *(13)* 118%	**0**- 12 *(19)* 158%	5,16748	0,0230
KR3 (%)	**67** – 63 *(33)* 52%	**43** – 47 *(31)* 66%	80,4616	0,0		KR3 (%)	**39** - 43 *(25)* 58%	**36**- 43 *(34)* 79%	0,205505	0,650
KR4 (%)	**6** – 18 *(24)* 133%	**26** – 30 *(26)* 87%	100,2	0,0		KR4 (%)	**30** - 34 *(23)* 68%	**21**- 31 *(29)* 93%	3,47577	0,062
KR5 (%)	**0** – 5 *(13)* 260%	**0** – 10 *(17)* 170%	79,5508	0,0		KR5 (%)	**5** - 10 *(14)* 140%	**0**- 13 *(21)* 161%	4,82345	0,028
VG0 (%)	**78** – 71 *(26)* 37%	**66** – 65 *(23)* 35%	31,7765	1,729E-8		VG0 (%)	**69** - 69 *(19)* 28%	**64**- 62 *(26)* 42%	3,25452	0,071
VG1 (%)	**0,07** – 1,5 *(4)* 267%	**0** – 0,5 *(2)* 400%	60,6622	0,0		VG1 (%)	**0** – 0,4 *(1)* 250%	**0** - 1 *(2)* 200%	47,3211	6,025E-12
VG2 (%)	**0,7** – 4,5 *(9)* 200%	**2,7** – 7 *(11)* 157%	51,7786	0,0		VG2 (%)	**4** - 8 *(10)* 125%	**1** - 6 *(10)* 167%	13,1145	0,0002
VG3 (%)	**4,7** – 12 *(17)* 142%	**4,4** – 9 *(12)* 133%	0,493289	0,482		VG3 (%)	**6** - 9 *(9)* 100%	**3** - 10 *(17)* 170%	4,13088	0,042
VG4 (%)	**8** – 11 *(10)* 91%	**15** – 18 *(13)* 72%	144,353	0,0		VG4 (%)	**13** - 14 *(9)* 64%	**18** - 22 *(16)* 73%	12,4996	0,0004
AI1 (%)	**48** – 49 *(31)* 63%	**36**– 38 *(26)* 68%	43,1784	4,996E-11		AI1 (%)	**37** - 40 *(23)* 57%	**29** - 34 *(29)* 85%	5,98626	0,0144
AI2 (%)	**34** – 33 *(19)* 58%	**43** – 42 *(18)* 43%	68,7045	0,0		AI2 (%)	**43** - 41 *(15)* 36%	**45** - 44 *(20)* 45%	1,75365	0,185
AI3 (%)	**11** – 18 *(19)* 105%	**16** – 21 *(16)* 76%	25,1706	5,247E-7		AI3 (%)	**17** - 19 *(13)* 68%	**14** - 22 *(19)* 86%	0,00263593	0,959

Table 5: Median, mean (standard deviation) coefficient of variation for each variable for WD values

Variables	Polygons with BAR equal to 0 (*)	Polygons with positive BAR (*)	Kruskal-Wallis Test	Probability		Variables	Polygons with Low BAR (*)	Polygons with High BAR (*)	Kruskal-Wallis Test	Probability
	Sample size: **1957**	Sample size: **1004**					Sample size: **335**	Sample size: **335**		
AGR (%)	**36**– 39 *(32)* 82%	**14**– 21 *(23)* 109%	210,107	0,0		AGR (%)	**20**–27 *(25)* 92%	**2** – 14 *(19)* 135%	66,8746	0,0
BOI (%)	**14**– 24 *(27)* 112%	**27**– 32 *(27)* 84%	65,2788	0,0		BOI (%)	**29**–32 *(24)* 75%	**22** – 30 *(28)* 93%	3,51177	0,0609
ESN (%)	**0**– 8 *(17)* 212%	**19**– 28 *(28)* 100%	662,639	0,0		ESN (%)	**7**–13 *(16)* 123%	**41** – 45 *(31)* 69%	193,243	0,0
URB (%)	**16**– 27 *(27)* 100%	**11**– 18 *(20)* 111%	68,053	0,0		URB (%)	**19**–27 *(23)* 85%	**6** – 10 *(14)* 140%	127,437	0,0
CRE (%)	**0**– 1,8 *(9)* 500%	**0**– 1,3 *(7)* 538%	0,642814	0,422		CRE (%)	**0**–1,7 *(7)* 412%	**0** – 1,1 *(8)* 727%	49,4125	2,074E-12
DB (h/km^2)	**56**–98–*(123)* 125%	**57**–95–*(115)* 121%	1,38164	0,239		DB (h/km^2)	**82**–141*(145)* 103%	**40** – 53 *(52)* 98%	149,826	0,0
DC (km/km^2)	**5,7**– 6,1 *(4,2)* 69%	**7,3**–7,8 *(4,5)* 58%	96,2323	0,0		DC (km/km^2)	**6,1**–6,4 *(3,5)* 55%	**8,7** – 9 *(5)* 55%	54,8355	0,0
DR (km/km^2)	**4,6**– 6 *(6,3)* 105%	**3,1**–4,3 *(4,8)* 112%	53,2006	0,0		DR (km/km^2)	**5,4**–6,4 *(5)* 78%	**0**–2,4 *(3,5)* 146%	128,703	0,0
EX1 (%)	**6**– 21 *(28)* 133%	**20**– 27 *(28)* 104%	59,6341	0,0		EX1 (%)	**19**–26 *(27)* 104%	**20**–27 *(28)* 104%	0,00091766	0,975
EX2 (%)	**53**– 52 *(29)* 56%	**51**– 52 *(26)* 50%	0,566681	0,451		EX2 (%)	**51**–51 *(25)* 49%	**53**–52 *(27)* 52%	0,361006	0,547
EX3 (%)	**17**– 27 *(30)* 111%	**13**– 21 *(24)* 114%	15,0574	0,0001		EX3 (%)	**14**–23 *(25)* 109%	**14**–21 *(24)* 114%	1,18457	0,276
PT (%)	**5**– 6,2 *(2,5)* 40%	**6,4**– 7,9 *(3,4)* 43%	300,269	0,00		PT (%)	**6** – 7 *(3)* 43%	**7** – 9 *(3)* 33%	7,19531	0,007
ALT (m)	**167**–166–*(107)* 64%	**201**–209 *(117)* 56%	69,587	0		ALT (m)	**185-**188*(108)* 57%	**241**–249*(132)* 53%	38,3255	5,987E-10
KR1 (%)	**0** – 1,1 *(6)* 545%	**0** – 1,9 *(6)* 316%	63,5622	0,0		KR1 (%)	**0** – 1,4 *(5)* 357%	**0** – 2,3 *(7)* 304%	3,64671	0,056

KR2 (%)	**0** – 11 *(20)* 181%	**7** – 15 *(20)* 133%	77,9068	0,0		KR2 (%)	**7** – 14 *(17)* 121%	**7** – 16 *(21)* 131%	0,121589	0,727
KR3 (%)	**79** – 69 *(32)* 46%	**43** – 46 *(30)* 65%	336,805	0,0		KR3 (%)	**48** – 50 *(28)* 56%	**37** – 43 *(31)* 72%	12,201	0,0004
KR4 (%)	**0** – 16 *(24)* 150%	**24** – 28 *(25)* 89%	260,061	0,0		KR4 (%)	**23** – 27 *(24)* 89%	**22** – 27 *(25)* 92%	0,107512	0,742
KR5 (%)	**0** – 3,4 *(11)* 323%	**0** – 9,3 *(17)* 183%	231,18	0,0		KR5 (%)	**0** – 8 *(14)* 175%	**0** – 12 *(20)* 167%	0,08918	0,765
VG0 (%)	**84** – 76 *(25)* 33%	**60** – 59 *(24)* 41%	343,165	0,0		VG0 (%)	**69** – 66 *(22)* 33%	**53** – 53 *(23)* 43%	52,2644	0,0
VG1 (%)	**0,07**–1,4 *(3,4)* 243%	**0,01**–1,3 *(4,4)* 338%	18,8287	0,00001		VG1 (%)	**0** – 1,3 *(4)* 307%	**0** – 1,5 *(6)* 400%	29,7249	4,979E-8
VG2 (%)	**0,6** – 4 *(8,3)* 207%	**2** – 6,4 *(10)* 156%	105,417	0,00		VG2 (%)	**3** – 7 *(9)* 128%	**1** – 4 *(9)* 225%	32,5063	$1,188^{E}$-8
VG3 (%)	**3,4** – 11 *(16)* 145%	**8** – 14 *(17)* 121%	117,674	0,00		VG3 (%)	**8** – 13 *(15)* 115%	**10**–16 *(18)* 112%	4,37655	0,0364
VG4 (%)	**6** – 8 *(8)* 100%	**16** – 19 *(12)* 63%	618,264	0,00		VG4 (%)	**12** – 13 *(8)* 61%	**23** – 25 *(15)* 60%	144,59	0,0
AI1 (%)	**57** – 55 – *(30)* 54%	**29** – 33 – *(25)* 76%	356,831	0		AI1 (%)	**36** – 40 *(25)* 62%	**19** – 25 *(23)* 92%	69,4389	0,0
AI2 (%)	**29** – 29 – *(19)* 66%	**44** – 43 – *(17)* 39%	335,852	0		AI2 (%)	**41** – 39 *(16)* 41%	**49** – 48 *(17)* 35%	42,7064	6,360E-11
AI3 (%)	**8** – 16 – *(18)* 112%	**22** – 24 – *(17)* 71%	307,196	0		AI3 (%)	**19** – 21 *(15)* 71%	**23** – 27 *(18)* 66%	22,5399	0,000002

Table 6: Median, mean (standard deviation) coefficient of variation for each variable for BAR values

Housing density (DB = 178 houses/km^2) was twice as high and road density (DR = 7 km/km^2) 1.4 times higher in polygons with a positive FID. Comparing low and high values of FID within these polygons, housing density was 5 times lower, road density 1.6 times lower but country road density was 1.3 times higher in the highest values of FID. FID was particularly high in areas with human activities (high housing and road densities). According to statistics, these human activities are the main cause of fire ignition. But within housing areas, FID was highest when housing and road densities were not so high. This apparent contradiction can be explained by the fact too high housing densities considerably decrease the proportion of available burnable vegetation and consequently the probability of fire ignition. For that reason, we noted higher levels of FID for average values of housing densities corresponding to isolated and scattered wildland-urban interfaces according to the values in figure 4. The country road density (DC = 7.2 km/km^2) was 10% higher in polygons with positive WD. Comparing low and high values of WD within these polygons, housing density was 5 times lower, road density 2.7 times lower but country road density was 1.3 times higher in polygons with the highest values of WD. The country road density (DC = 7.8 km/km^2) was 1.3 times higher but road density (DR = 4.3 km/km^2) was 1.4 lower in polygons with positive BAR values. Comparing low and high values of BAR within these polygons, housing density and road density were 2.7 times lower but country road density was 1.4 times higher in polygons with the highest BAR values. These results showed that within fire risk areas, isolated and scattered WUI areas were at higher risk based on the three variables examined (FID, WD and BAR). The examination of the other variables highlighted the human and natural environment that increases wildfire risk.

Figure 6 illustrates the other results comparing low and high levels of FID, WD and BAR presented in tables 4 to 6.

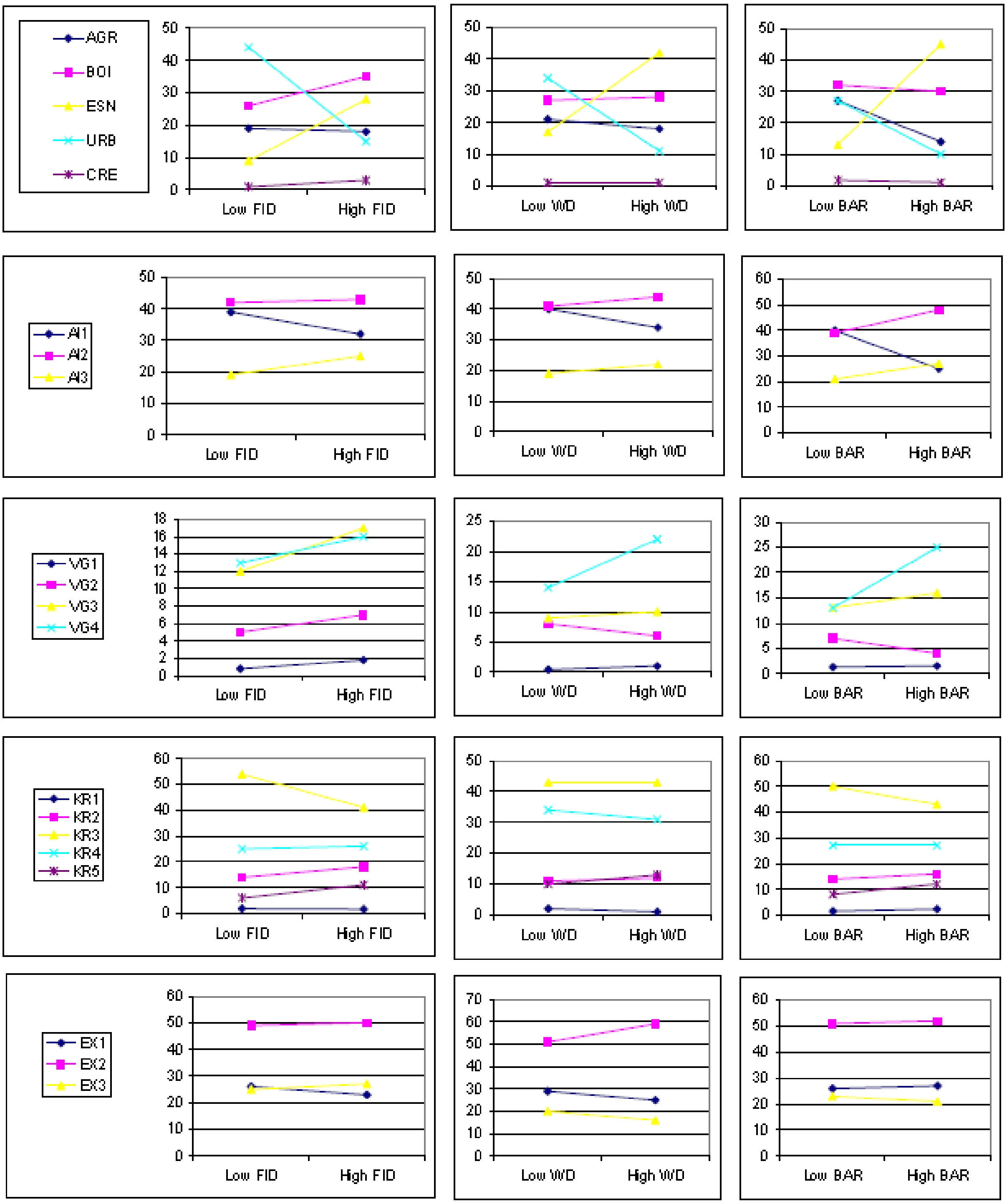

Fig 6: Comparison of risk levels through the FID, WD, BAR values per main variable

In polygons with a positive FID, the proportion of agricultural area (AGR = 18%) was 1.8 times lower but the proportion of forested area (BOI = 32%) and other natural area (ESN = 18%) was 1.2 times higher and urban area (URB = 30%) was 1.3 times higher than in polygons with zero FID values. Comparing low and high values of FID within these polygons, the proportion of other natural area was 3 times higher and of urban areas 3 times lower in for the highest values of FID. In polygons with a positive WD, the proportion of agricultural area (AGR = 22%) was 1.5 times lower and of urban area (URB = 20%) 1.25 times lower but the proportion of other natural area (ESN = 29%) was 2.2 times higher than in polygons with zero WD values. Comparing low and high values of WD within these polygons, the proportion of other natural areas was 2.5 times higher but the proportions of agricultural and urban areas were respectively 1.2 and 3 times lower for the highest values of WD. In the same way, in polygons with positive BAR, the proportion of agricultural area (AGR = 21%) was 1.9 times lower and of urban area (URB = 18%) 1.5 times lower, but the proportion of forested area (BOI = 32%) was 1.3 times higher and the proportion of other natural areas (ESN = 28%) was 3.5 times higher than in polygons with zero BAR values. Comparing low and high BAR values within these polygons, the proportion of other natural areas was also 3.5 times higher but the proportions of agricultural and urban areas were respectively 2 and 2.7 times lower for the highest values of BAR. These results also showed that the proportion of urban areas was consistent for fire ignition (mainly for FID) and a large proportion of forested and other natural areas (more than 50 %) was also characterized by FID, WD, BAR. And in the same way as before, the values of the indicators FID, WD, BAR increased with an increase in the proportion of natural areas and a decrease in urban areas corresponding to a balance between the proportion of existing human activities and of a sufficient quantity of burnable vegetation available in the same area.

The variable corresponding to the value of the aggregation index of vegetation changed in the same way for the three indicators FID, WD, BAR. The proportions of the low and high aggregation indexes (AI2 & AI3 around 66%) were higher in polygons with a positive value. Comparing low and high values within these polygons, the proportion of aggregation indexes equal to zero (AI1) was slightly lower for the highest values of FID, WD, BAR and the proportion of low and high aggregation indexes (AI2 & AI3) was higher. These results are consistent with results reported above.

The proportion of vegetation was higher in polygons with a positive FID but there was no significant difference in the nature of vegetation for the highest values of FID. In polygons with a positive WD, the proportions of shrubland (garrigue) (VG4 = 18%) and mixed hardwood-coniferous vegetation (VG2 = 7%) were higher but the proportion of resinous vegetation (VG3 = 9%) was lower in polygons with a positive WD. Comparing low and high values of WD within these polygons, the proportion of garrigue was again higher at the expense of mixed vegetation for the highest values of WD. The proportions of coniferous vegetation (VG3 = 14%) and garrigue (VG4 = 19%) were higher in polygons with a positive BAR. Comparing low and high values of BAR within these polygons, the proportion of garrigue (VG4 = 25%) was higher for the highest values of BAR.

The proportions of cool (KR2 = 17%), hot (KR4 = 24%) and very hot (KR5 = 8%) exposure were higher in polygons with a positive FID. Comparing low and high values of FID within these polygons, the proportions of very cool (KR1) and neutral (KR3) exposures were lower but the proportion of very hot exposure was higher for the highest values of FID. The proportions of hot (KR4 = 30%) and very hot (KR5 = 10%) exposure were 2 times higher in polygons with a positive WD. Comparing low and high values of WD within these polygons, the proportion of very hot exposure was 1.3 times higher for the highest values of WD. Finally, the proportion of hot and very hot exposure were most frequent in polygons with positive BAR and for the highest values of BAR.

There were no statistically significant differences in FID, WD and BAR values for the other variables in the situations analyzed.

Discussion

The results of the analysis of the characterization of the natural and human environment of the types of territory and particularly the types of WUI enabled us to establish an identity card for each type of territory. This first analysis showed that isolated and scattered WUI areas had a higher risk based on the three indicators examined: FID, WD and BAR. Subsequently, characterization of the natural and human environment with respect to different levels of fire risk confirmed the results of relationships already partially revealed in Lampin-Maillet et al. (2010) between spatial distribution of fire ignition points and wildfires and the territory as a whole: a higher level of risk was observed in wildland-urban interfaces. The highest values of FID, WD and BAR were observed in isolated and scattered WUI. These observations were also explained by the results of the analysis of human variables with respect to housing and road density. These results revealed an apparent contradiction already noted by other authors. In fact, the fire ignition density values were higher in areas with a high housing density but decreased in a statistically significant way from types of territory with low housing density to types of territory with very high housing density. Fire ignition density was lowest outside built-up areas (housing density equal to zero and low road density). Fire ignition density was high in built-up areas and increased with a decrease in housing and road density and in areas where housing was sparse: values were higher in isolated WUI than in clustered WUI. A positive housing density revealed human activity, which is the main cause of fire ignition, but very high housing density markedly reduced the proportion of burnable vegetation present and, as a result, the probability of fire ignition. In the same way, Mercer & Preston (2005) showed that variables related to WUI were significantly linked with an increase in fire ignition, that increasing housing density was linked with fewer cases of fire ignition, and that very high density housing areas tended to have a lower risk of fire. Syphard et al. (2007 a, b) showed that for the number of fires, the proportion of intermixed WUI (corresponding to isolated and scattered WUI in our study) explained more variation than any other variable, suggesting that the spatial pattern of housing development and fuel are important risk factors for fire ignition. These authors assumed that fire risk may be higher at intermediate levels of urbanization. In our study, within wildland-urban interfaces, fire ignition density was significantly higher in WUI in contact with low and high aggregation values of vegetation (sparse but also continuous vegetation such as forested stands and shrubland) than in WUI in contact with zero aggregation values of vegetation (agricultural areas, bare ground, etc.). However fire ignition density was not equal to zero even if aggregation of vegetation was nil, which is in agreement with the results of Sturtevant & Cleland (2007), who reported that fires could be observed in agricultural areas associated with rural housing and that a small proportion of agricultural areas mixed with forested areas could increase probability of fire ignition (Radeloff et al., 2005b).

Like for FID, wildfire density values were the highest in built-up areas and within the built-up areas, WD values increased with a decrease in housing and road density and when the proportion of built-up areas was lowest, with higher values in isolated WUI than in clustered WUI. Like FID and also involving an apparent contradiction, wildfires were more frequent in areas with intermediate levels of human activity corresponding to isolated and scattered wildland-urban interfaces as a function of the spatial housing configuration and fuel (Keeley, 2005; Syphard et al., 2007b; Cardille et al., 2001; Pew & Larsen, 2001). As reported by Syphard et al. (2007a, b), there is a threshold above which wildfire frequency linked to increasing fire ignition is counterbalanced by the reduction in available fuel in urbanized areas. In the present study, the high proportion of forested areas and shrublands affected by high positive WD values was clear and consistent. Mixed vegetation and shrubland (garrigue), corresponding to sparse vegetation, were particularly concerned. This result could be explained by the fact that 25 years are needed for a resinous stand affected by wildfire to regain its forested state. Therefore wildfire density values are lower in forested areas because of the absence of new forest stands but are higher in shrubland (garrigue), which regain its initial state three years after a fire. Finally hot - and particularly very hot - exposures are affected by wildfires, as already demonstrated by Vasquez & Moreno (2001), who showed that fires usually occur on slopes exposed to the south.

The burned area ratio (BAR) was generally higher outside built-up areas. It is clear that wildfires mainly affect wildland areas but when built-up areas are concerned by wildfires, isolated and scattered WUI are the types mainly affected. In these WUI, the proportion of forested and other natural areas is high enough to enable propagation of wildfire. These values increased with a decrease in housing and road density corresponding to a more forested and natural environment: values were thus higher in isolated WUI in contact with continuous vegetation than in clustered WUI. In the same way as for WD, the burned area ratio appeared to be higher in areas with intermediate levels of human activity corresponding to isolated and scattered wildland-urban interfaces. Mercer & Preston (2005) already showed that variables related to WUI were significantly linked with more burned areas, that increasing housing density was linked with less burned areas, and that very high density housing areas tended to be less burned. The burned area ratio was lowest in built-up areas located outside WUI, areas that are normally less concerned by fire risk (in these areas clearing brush is not mandatory, for example). This type of territory comprised about 10% of forested and other natural areas and more than 35% of urban areas, and the proportion of burnable and continuous vegetation was too low for wildfire propagation. Syphard et al. (2007a) also reported that a landscape composed of less than 30% of forested and other natural areas significantly decreased the spread of fire because of the discontinuity of fuel vegetation. In the present study, this was the case for built-up areas outside WUI and clustered WUI.

The proportion of low and high aggregation of vegetation corresponding to sparse and continuous vegetation was high for high values of FID, WD and BAR. This confirmed the importance of the availability of burnable vegetation, which may be fragmented and sparse, or not. In fact, fires are not stopped despite the fragmentation of vegetation that characterizes urban zones (Syphard et al., 2008) and particularly clustered WUI areas, but the speed of fire spread can be reduced more easily (Brosofske et al., 2007). But an increase in fragmentation linked with urban activities can decrease fuel continuity and fire propagation (Davis & Burrows, 1994 in the Californian chaparral; Duncan & Schmalzer, 2004 in Florida). Syphard et al. (2008) showed that more fires spread away from human activities and human infrastructures where vegetation was more continuous. Part of the burned area ratio also depends on the type of vegetation, i.e. forested stands, shrubland, or grass, (Syphard et al., 2007b). Our results highlighted the high proportion of garrigue concerned by fires. Finally very hot exposure, steep slopes and elevation were most affected by wildfires, as already demonstrated by Vasquez & Moreno (2001), who showed that fires usually occurred on dry slopes at higher elevations.

These results have interesting implications for fire prevention and land management as they emphasize the fact that it is appropriate to deploy specific prevention actions in WUI, particularly in isolated and scattered WUI. Although these two interfaces represent the smallest areas in our study (Lampin-Maillet et al., 2010), they are most concerned by fire hazard (high fire ignition density and wildfire density) and they are most vulnerable to fire (high burned area ratio). Focusing resources on prevention in these areas, improving the awareness of inhabitants in these sensitive but limited areas could prevent some serious consequences in terms of damage by fire, and dramatically improve the efficiency of fire prevention. This will globally decrease the risk of fire (i) by reducing fire propagation *via* biomass removal, and (ii) by reducing fire ignition probability by encouraging less carelessness. Accomplishing this goal is strictly related to the designation of suitable prevention messages and preventive measures which can be different according to WUI types.

Therefore it is important to insist on the fact that in case of fire, the isolated and scattered WUI are protected by fire-fighters with more difficulties than the clustered WUI: they are more all over the place in the landscape, generally networked by narrow country roads and in a natural burnable environment. Even if our results pointed out these areas as very risky it can be conceivable to concentrate their fire-fighting forces near these riskiest areas to be able to attack a fire as quickly as possible. So inhabitants have to be prepared to assume their home protection as well as possible in prevention. So in terms of forest and fire management, the strengthening of individual or collective protective actions are recommended (clearing brush by removing biomass, and pruning trees) to interrupt the horizontal and vertical continuity of vegetation and thus mitigate fire propagation. In terms of land management, isolated housing should be avoided and compact urban development and densification of housing encouraged. These preventive measures should help decrease the level of fire risk in the main WUI concerned.

WUI have increased considerably worldwide in recent decades and this trend will certainly continue in the coming years due to the pursuance of the land abandonment process combined with urbanization. Focusing resources in this way could be all the more profitable given the expected changes in WUI dynamics and associated fire risk in the context of ongoing changes in climate, urbanization and vegetation.

Conclusion

In this paper, we described the spatial and statistical characteristics of the land cover of wildland-urban interfaces exposed to wildfire risk. Assuming that the three indicators “fire ignition density, wildfire density and burned area ratio” correspond to important aspects of fire risk (based on data in the literature), we showed that, at least in the south of France, wildland-urban interfaces are in fact at high risk of wildfire. To reach this conclusion, we examined the relationships between the three above-mentioned indicators and the landscape characteristics of a specific area in the south of France. We showed that among the different types of wildland-urban interfaces, isolated and scattered WUI are the most affected by high fire risk. Their main land cover characteristics, i.e. low housing and road densities but high country road density, burnable vegetation such as forested stands and shrublands (garrigue) probably explain the high fire risk.

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