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Research article

Mapping regional patterns of large forest fires in Wildland–Urban Interface areas in Europe

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ABSTRACT

Over recent decades, Land Use and Cover Change (LUCC) trends in many regions of Europe have reconfigured the landscape structures around many urban areas. In these areas, the proximity to landscape elements with high forest fuels has increased the fire risk to people and property. These Wildland–Urban Interface areas (WUI) can be defined as landscapes where anthropogenic urban land use and forest fuel mass come into contact. Mapping their extent is needed to prioritize fire risk control and inform local forest fire risk management strategies. This study proposes a method to map the extent and spatial patterns of the European WUI areas at continental scale. Using the European map of WUI areas, the hypothesis is tested that the distance from the nearest WUI area is related to the forest fire probability. Statistical relationships between the distance from the nearest WUI area, and large forest fire incidents from satellite remote sensing were subsequently modelled by logistic regression analysis. The first European scale map of the WUI extent and locations is presented. Country-specific positive and negative relationships of large fires and the proximity to the nearest WUI area are found. A regional-scale analysis shows a strong influence of the WUI zones on large fires in parts of the Mediterranean regions. Results indicate that the probability of large burned surfaces increases with diminishing WUI distance in touristic regions like Sardinia, Provence-Alpes-Côte d'Azur, or in regions with a strong peri-urban component as Catalunya, Comunidad de Madrid, Comunidad Valenciana. For the above regions, probability curves of large burned surfaces show statistical relationships (ROC value > 0.5) inside a 5000 m buffer of the nearest WUI. Wise land management can provide a valuable ecosystem service of fire risk reduction that is currently not explicitly included in ecosystem service valuations. The results re-emphasise the importance of including this ecosystem service in landscape valuations to account for the significant landscape function of reducing the risk of catastrophic large fires.

1. Introduction

Europe has experienced extreme wildfires in the past decades. In European forest fire management, WUI areas have become the focus of attention because of the high economic damage and the risks to people from raging wildfires in the immediate vicinity of urban settlements. In some countries, the total WUI area is increasing due to land cover and land use change, with farmland being taken out of agricultural use, shrub encroachment is providing additional fire fuel, and cities expanding into previously unoccupied areas further reduce the distance to fire-prone areas.

Forest fires have a strong negative impact on the WUI zone (Alexandre et al., 2015; Penman et al., 2014; Kanclerz and DeChano-Cook, 2013). The urban land use in a rural context combined with uncontrolled growth of forest fuel increases the probability of the fire hazard (Badia and Pallares, 2006). The WUI areas are particularly vulnerable to forest fires because local communities are often not sufficiently prepared for a possible forest fire (Goemans and Ballamingie, 2013). The wildfire response is strictly related to the social local context of WUI community. The rural WUI communities are characterized with a higher personal ability to reduce fire risk respect the WUI urban communities (Paveglio et al., 2015). In the

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context of forest fire reduction these areas must be considered by specific plans due to the highly disastrous building loss from fire (Lafortezza et al., 2015; Manzello and Foote, 2014).

European socio-economic trends are resulting in changing spatial landscape structures, in areas where there is urban and anthropogenic infrastructure growth or urban sprawl (Catalán et al., 2008) along with successive fragmentation of woodland (Antrop, 2000; Salvati et al., 2013). At the same time, rural abandonment is resulting in a disproportionate increase in fuel mass (Moreira et al., 2001). Important LUCC processes have impacted on many European countries in the last decades. Artificial land areas are growing and in parallel woodlands are increasing on abandoned former farmland areas (EEA, 2010).

In this study we consider 'large fire', defined not only by their size and intensity but also by their strong socio-economic impact in WUI areas (Stephens et al., 2014) and serious environmental consequences (Williams et al., 2011). The identification of a WUI can support an effective European fire risk management policy, reducing the risk and its associated economic costs. The mapping of WUI areas at European scale is crucial in order to understand the regional patterns of fire risk vulnerability and to estimate the damage costs of fires for local communities there (Lowell et al., 2009).

A systematic analysis of WUI areas was already undertaken in North America, when the strong impact of wildfires on urban settlements triggered an alarming social resonance (McCaffrey et al., 2011). Therefore, in the USA an official definition of WUI areas and a standardised WUI mapping was produced in accordance with the development of a legal forest framework. The first official definition of WUI was coined by the U.S. Department of Agriculture and U.S. Department of Interior (1996) as areas where interacting human structures and forest fuel come into contact. WUI mapping was developed in the USA due to the urgent need to improve risk assessment. In the USA an advanced legal forest framework and high spatial data availability facilitate cartographic map production at large scale. In North America the techniques implemented to map WUI zones are based on an evaluation of the urban density and vegetation density per km^2.

Census data and a national land cover map provide data sources for US studies of WUIs. At the same time, the legal framework in the US provides an analytical definition of the WUI, characterised by an urban density greater than 6.17 houses/km^2 and 50% or more vegetation cover in an area of 5 km^2 around the urban perimeter zone of width 2.4 km (USDA and USDI, 2001). Radeloff et al. (2005) converts this legal definition to a cartographic product by GIS analysis and presents a sensitivity analysis by doubling and halving the original threshold values expressed by law, observing that the WUI area mapping is most susceptible to the housing density threshold.

However, the size and dimensions of the WUI areas are closely dependent on landscape features, landscape structure and forest fragmentation (Chas-Amil et al., 2013). Bar-Massada et al. (2013) applied different buffer zones around settlements in order to detect the relative WUI area variability. The author highlighted that the spatial extension of a WUI area is defined by the combination of several regional landscape features. Peters et al. (2013) produced a WUI map that considered the housing density and vegetation value as expressed by the legal framework to calculate the fire probability for the WUI areas using a moisture index. Theobald and Romme (2007) compared a WUI map with the wildfire hazard and verified that more than 65% of WUI areas in the US are located in areas labelled as having a 'severe fire regime'. However, a detailed WUI map at the local scale in North America can also be useful without making any reference to national spatial data infrastructures. For this propose, Cleve et al. (2008) published a local WUI map for a small community of California (Napa County) from aerial photographs with 15 cm spatial resolution.

In recent years, WUI mapping approaches have also been developed in Europe (Galiana-Martin, 2012), though at the large scale it is a complicated by the heterogeneous laws and administrative organisations and the scarcity of standardised geo-data. Wadsworth et al. (2008) discuss the difficulties in reconciling semantic differences between land cover maps generated for different purposes and following diverse class definitions. The current European approaches to mapping and classifying the WUI have in common that they analyse the landscape characteristics defined by urban settlement and vegetation. Indeed, analysing the landscape composition, Lampin-Maillet et al. (2010) defined the WUI in accordance to French forest law 2001/602. In this case the WUI area is the zone surrounding forest and scrubland vegetation up to a maximum distance of 200 m. In Europe the regional forest plans change from region to region, fixing the respective value of buffer distance from urban settlements and vegetation areas.

Different WUI mapping approaches implement different distance buffers and classify the WUI areas from a combination of urban and vegetation features in the landscape. In Spain several authors have classified the WUI areas at regional or sub-regional level. Chas-Amil et al. (2013) mapped WUI areas based on the Galician statute that defines a buffer distance of 400 m from vegetation and 50 m around urban land. In this case the authors make a classification of the WUI typology, recognising that the WUI composition changes with the distance from larger cities. In the Community of Valencia, a WUI mapping exercise was carried out (Galiana-Matin et al., 2011; Madrigal et al., 2013) with a similar method to Lampin-Maillet et al. (2010). The characterisation of WUI areas in the Madrid region by Herrero et al. (2012) finds that the wildfire incidence is higher among isolated residential houses than in the proximity of compact urban areas. For Spain, Caballero et al. (2007) presents a national approach defining 17 typologies of WUI based on relationships between vegetation characteristics and urban areas.

In Europe, a common legal framework to define WUI areas for practical fire risk management and spatial planning does not yet exist. Therefore, it is currently not possible to produce a cartographic map of fires in WUI areas across all European regions in a manner that is consistent with all regional definitions. In the geographical analysis of environmental risk, before mapping risk factors it is good practice to check the legal framework to identify the analytical parameters that define the phenomena under study. The interpretation and use of WUI definitions have a direct implication for the development of operational mapping. The mapping methodology changes according to the studied region, the scale adopted and the data availability (Platt, 2011).

Related to the difficulties inherent in defining the concept of the WUI, the spatial scale of the investigation needs to be considered. Several studies have mapped WUI areas considering only a small study area and focussing on the individual building scale. Here, we consider the European continental scale and not only the residential areas but the conjunction of all artificial surfaces that are in contact with forest fuel mass. Population density is not considered, because other artificial surfaces such as industrial estates and factories are of high commercial value and fire risk is very relevant to them for asset protection and property insurance.

In the WUI mapping approach, the graphic representation must match a clear conceptual definition of what and where the WUI is (Stewart et al., 2007). Considering the aim to map the WUI areas at a continental scale, we use the definition of WUI developed by FAO (2002, p.73), as 'the transition zone between cities and wildland, where structures and other human development meet undevelopment wildland or vegetative fuels'.

The study aims to quantify the burned area extent at continental scale in the WUI areas of Europe. More precisely, we consider the interaction between large forest fire incidences and WUI areas, since these are characterized by intense human pressure on fuel mass. This aim creates the need to standardise the approach to WUI mapping with a consistent buffer distance and a harmonised land cover dataset. WUI maps can be derived in many different ways, and there is currently no consensus on an agreed cartographic WUI representation because at the local scale, user needs vary between Europe's regions (Stewart et al., 2009).

The objectives of this study were to:

(i) Map the extent of European WUI areas at continental scale, producing a cartographic map based on Corine Land Cover 2006 (CLC).
(ii) Identify the relationships between WUI areas and occurrences of large fires (burned surfaces).
(iii) Model empirical relationships between the extent of large fires in the WUI in different European regions/countries to test for regional heterogeneity.

2. Methods and data

The method follows two principal steps. First, the spatial locations and extent of European WUI areas are mapped at continental scale. Second, empirical data are tested statistically for any regional patterns of large fire occurrences within the WUI areas (Fig. 1).

2.1. Study area

The overall study area covers the entire European Union, including the non-member states of Switzerland, Norway, Iceland, Montenegro, the Former Yugoslav Republic of Macedonia, Turkey, Bosnia and Herzegovina Kosovo, but not the EU member Greece for which CLC 2006 data were not available at the time of analysis (Fig. 2). WUI mapping and the cross-national scale statistical analysis between WUI distance and large forest fires were performed for the whole study area. Amongst the included countries, forest fires are strongly concentrated in the Mediterranean countries (Ganteaume et al., 2012). Accordingly, the national and regional-scale analyses targeted only the administrative units which undergone at least 10 large fires (Fig. 2).

2.2. Data

For the purpose of mapping the WUI areas at European scale, the harmonised land use/land cover map CORINE 2006 (CLC) is the only available consistent spatial dataset. To analyse forest fire regimes in the WUI the Burned Surfaces Product (BSP) by the European Commission (2010), Joint Research Centre (San-Miguel-Ayanz et al., 2013a), in the framework of the European Forest Fire Information System (EFFIS, 2014) was used. This dataset is consistently available at continental scale for the last decade (http://forest.jrc.ec.europa.eu/effis/).

The CLC is a commonly used reference dataset for European continental scale assessments of the environment, because it uses a generic definition of land cover classes throughout Europe. Such harmonised data also have multiple applications not only in environmental risk studies, but also in social and economic analysis (Stuczynski et al., 2009), transport management (Suau-Sanchez et al., 2013), and demography studies (Goerlich and Cantarino, 2013).

According to the INSPIRE directive 2007-2-EC (EU, 2007) CLC is one of the most prominent harmonised European datasets. CLC has accomplished both technical and semantic standardisation. In this paper we use the CLC 2006, 100 m spatial resolution raster data with a minimum mapping unit of 25 ha.

BSP is produced by EFFIS (2014) using MODIS images with a spatial resolution of 250 m and a temporal coverage from 2002 to 2013, with a minimum burned surface of 40 ha (European Commission, 2010). Large fires were considered because they

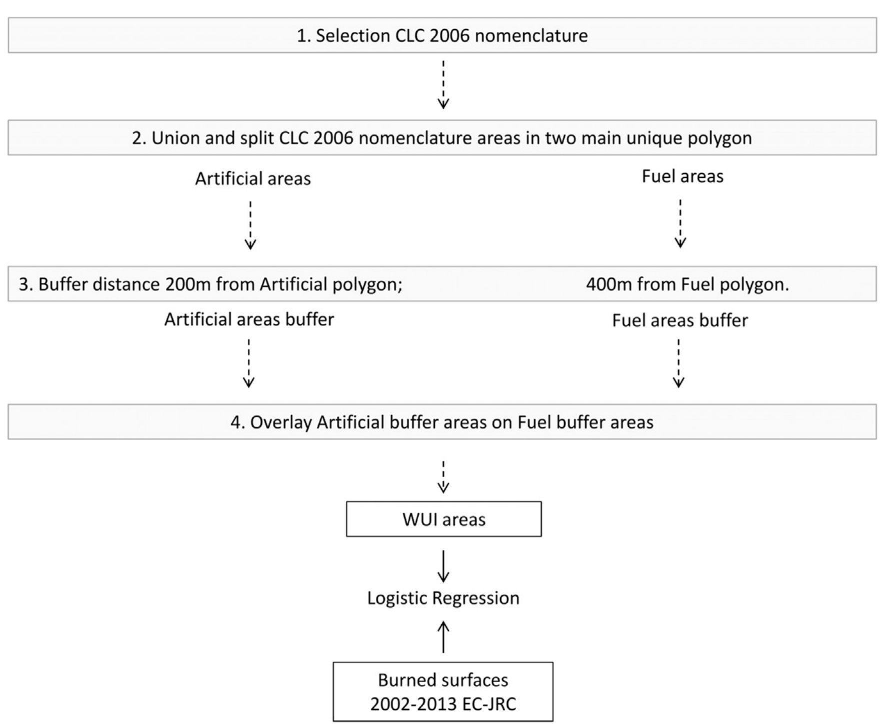

Fig. 1. General workflow of the mapping of WUI areas from CLC 2006.

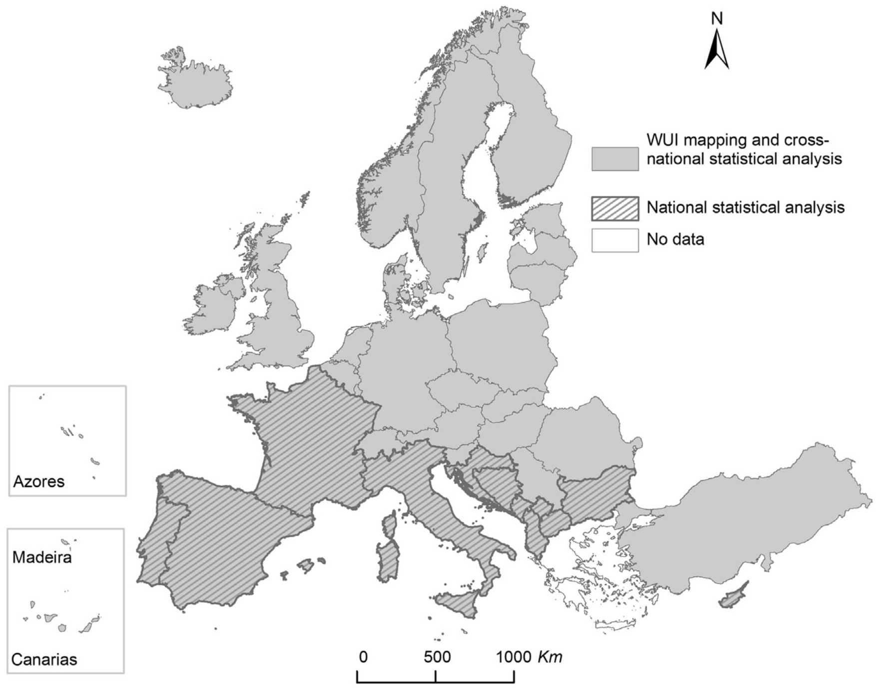

Fig. 2. Study area showing all the European countries covered by CLC 2006.

pose the greatest risk and potential economic damages (Adams, 2013).

The administrative boundaries were downloaded from the Global Administrative Areas database (GADM version 2.0, 2012). The Nomenclature of Territorial Units for Statistics (NUTS) NUTS-1 National level, and NUTS-2 regional level stratification were used for statistical analyses (EC, 2013). These selected databases represent the best compromise between cross-national territorial coverage and standardization level. However, these are subject to some limitations. For instance, the minimum fire size of the BSP product may omit some important fires smaller than the threshold (EFFIS, 2014), while the CORINE with a minimum mapping unit of 25 ha may miss small-scale land cover parcels leading to bias in the identification of WUIs at the smaller scale, especially in peri-urban areas (Diaz-Pacheco and Gutiérrez, 2013).

2.3. WUI mapping

In order to map WUI areas, a fixed buffer zone between urban and woodland areas was defined. We analysed the WUI definitions in different legal frameworks. At European level, the Regulation EC no. 2152/2003 denominated 'Forest Focus' does not make specific reference to the buffer distance between urban area and wildland to define the WUI. A further analysis at national level suggests that every country and region has its WUI interpretation with respective buffer distances. In some cases WUI areas are not mentioned explicitly in these documents, using shrub areas around urban settlements to define priority zones for fire risk management. Table 1 shows a synthesis of the buffer distance expressed by the national legal frameworks for European Mediterranean countries which have given the highest priority to forest fire management.

There is no transnational legislation that defines WUI areas for all European countries that is as harmonised as the CLC. The multilevel governance structure has generated a very heterogeneous legislative landscape. The European Union influences wildfire legislation through EC regulations, but every nation and region produces their own forest protection policies. This is especially evident in decentralised countries where local governments develop their own forest fire plan (Silva et al., 2010). In Portugal and France the centralised administrative organisation provides a unique definition of the WUI. In these countries the WUI areas are identified as the overlay of a buffer zone of 100 m around urban areas and 200 m around vegetation land cover (Assembleia da República Portuguesa, 2004; Republique Française, 2001). In Italy and Spain, where the decentralised governance structures have delegated authority over forest management to the regions, there are diverse WUI definitions (Ministerio de la presidencia Espanya, 2003; Parlamento Italiano, 2000). The buffer distances around urban settlements vary from 50 to 200 m and 100 to 400 m around woody vegetation covered areas.

Considering European law and the previous mapping studies presented in the literature, we can translate the definitions of WUI to a geospatial analysis method by implementing the most stringent parameters with the large buffer zones, giving the most inclusive WUI scenario. This ensures that no areas exposed to high fire vulnerability are overlooked in the analysis. Hence, a buffer

Table 1
Legal frameworks with reference the spatial definition of WUIs.

Countries	WUI distances adopted	Reference law
France	100 m urban settlement; 200 m around vegetation areas.	- French Forest Law 9/July/2002
Italy	50–200 m urban areas; 200 m–400 m around vegetation areas, depend to local region.	- Framework Law on forest fire 2000/353 and regional planes.
Portugal	100 m urban areas; 200 m around vegetation areas, Intervention Priority zone.	- National forest law against forest fire 30 June 156/2004.
Spain	50–100 m around urban areas; 100 m–400 m around vegetation areas, depend to local region.	- Ley de Montes 43/2003 and regional planes.

Table 2
CLC 2006 nomenclature of the selected classes to represent the two main layers, artificial areas and fuel areas.

Artificial areas	Code	Fuel areas	Code
Continuous urban fabric	1.11	Broad-leaved forest	3.11
Discontinuous urban fabric	1.12	Coniferous forest	3.12
Dump sites	1.32	Mixed forest	3.13
Industrial or commercial units	1.21	Sclerophyllous vegetation	3.23
Construction sites	1.33	Transitional woodland-shrub	3.24
Sport and leisure facilities	1.42		

The geospatial analysis procedure requires as a first step the merging of two main data layers representing wildland areas with forest fuels and urban areas. These two layers were generated from the selection of level 3 land cover classes from CLC 2006 shown in Table 2.

This approach ensures that all significant human built up surfaces are included in the analysis, and not just residential areas. It is important to consider industrial areas, commercial units and other areas, too. The European WUI areas were identified according to the FAO definition described above. Two data layers were created from the level 3 classification of CLC 2006: artificial areas and fuel mass areas.

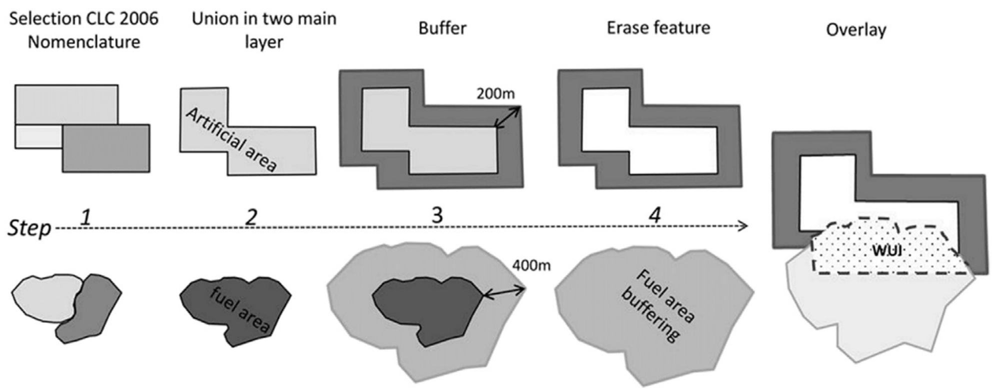

Fig. 3. Graphic representation of GIS analysis to generate the WUI map.

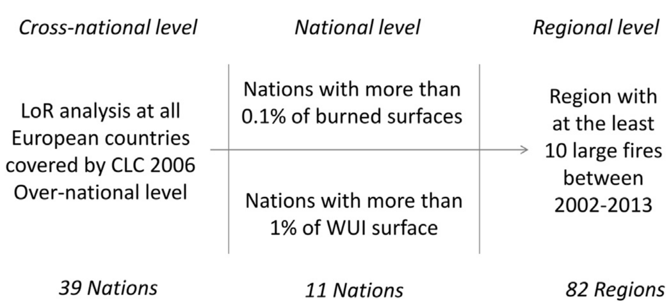

Fig. 4. Filtering operation in study area at the three studied spatial scales.

The first phase of our geospatial processing chain (Figs. 1 and 3) is based on the selection of all CLC classes that represent artificial surfaces and vegetation-fuel areas respectively. In the second step the classes were merged into two main layers, and in the third step a buffer of 200 m was created around artificial areas and 400 m around fuel areas. In the fourth step the two buffered data layers were overlayed to identify the overlapping areas as the WUI.

distance of 400 m from fuel mass and 200 m from artificial land was adopted here. WUI areas were mapped by intersecting the artificial surfaces buffer and the fuel surfaces buffer.

2.4. Statistical analyses

Statistical analyses at cross-national level were carried out to search for relationships between the European burned surfaces dataset as a function of the distance to the nearest WUI area. Further statistical analyses at national and regional level were performed to observe the scale-dependency. Filtering operations

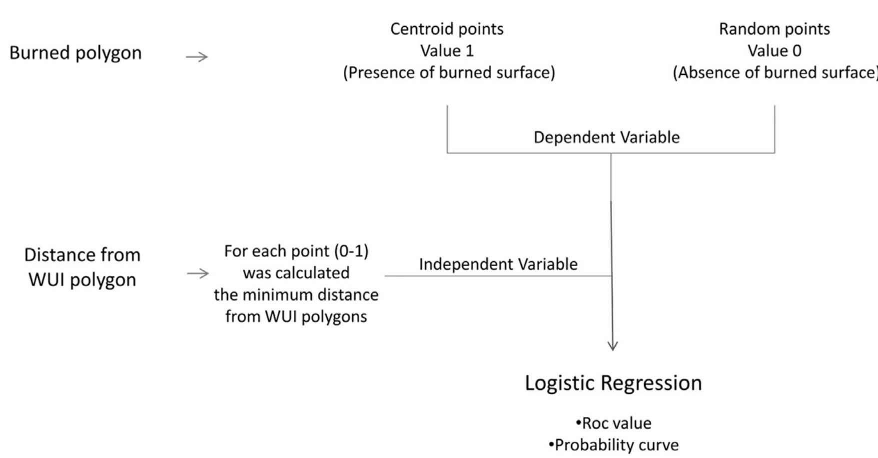

Fig. 5. Diagram showing the methodology for statistical analysis.

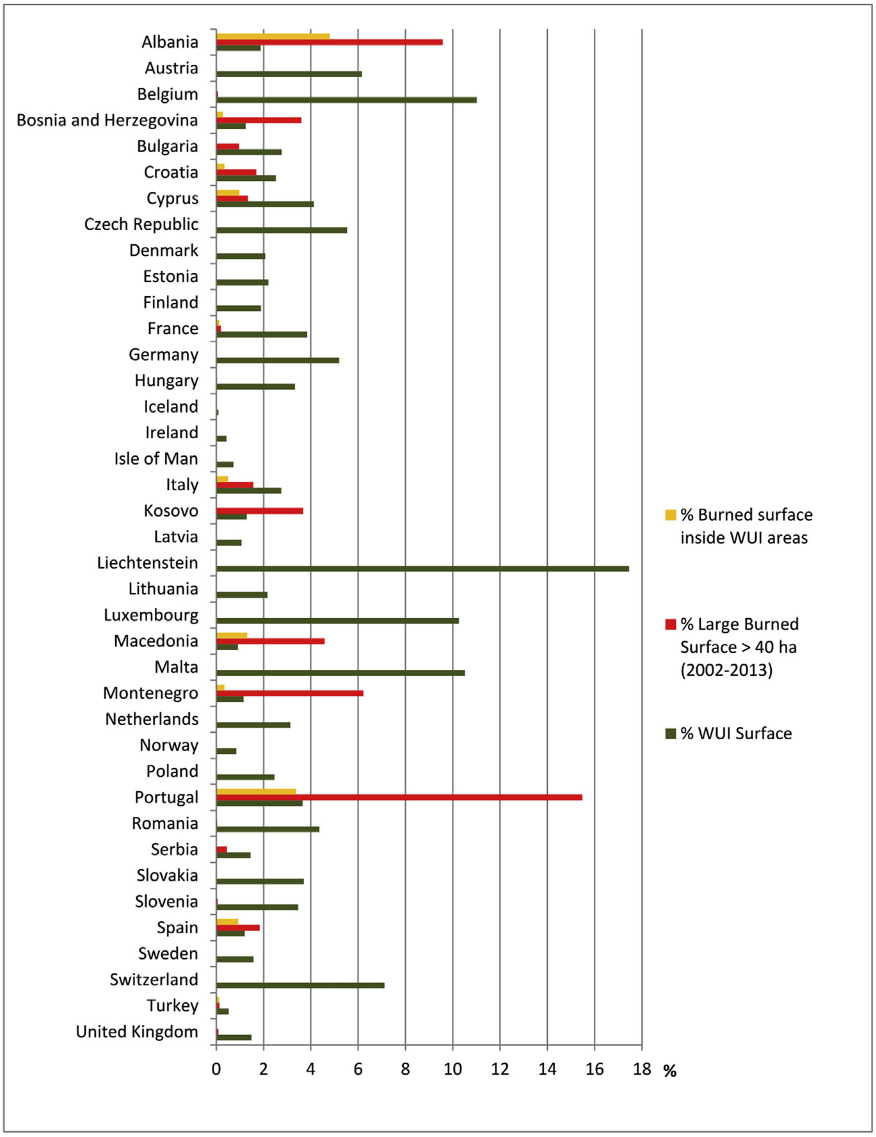

Fig. 6. Percent surface cover at national level of: WUI areas; burned surfaces inside WUI areas; all large burned surfaces (2002–2013).

were performed to reduce statistical noise in the data, caused by low fire occurrences or low presence of WUI areas. Accordingly, the national scale analysis was performed only for those countries where the burned surfaces and WUI areas were larger than 1% and 0.1% of the national land surface, respectively (Fig. 4). At regional level, only the regions experiencing more than 10 forest fire events between 2002 and 2013 were considered.

A logistic regression models (LoR) was applied (Fig. 5) to model the relationship between burned surfaces and the independent explanatory variable distance to the nearest WUI. This model expresses the probability of presence/absence of the dependent variable, large burned surfaces, as a function of the values of the independent variable. The LoR is able to express the probability value in a range from 0 to 1 by the area under the Receiver-Operating Characteristic curve (ROC) (Kedem and Forkianos, 2005; Kleinbaum and Klein, 2010). In accordance with this indicator, the discrimination threshold is fixed at 0.5. Above this value the ROC indicator shows a strong correlation. This statistical methodology has been applied to forest fire risk analysis, where the dependent variable has been represented by different variables such as density of burned surfaces (Martinez et al., 2009), presence of burned areas (Vilar et al., 2010) or considering the points of ignition (Badia et al., 2011). In our case, the burned areas were translated into points by the extraction of the centroid of the polygons. This generalisation allows a count of the centroid points which corresponds to the number of large burned areas.

The variables were extracted by the Spatial Analyst (ArcGIS 10.1) and the statistics calculated in SPSS 20.

3. Results

3.1. WUI distribution at European scale

The map of the extent of the European WUI is shown in Fig. 7. The WUI distribution is represented by a WUI map showing percent WUI surface in each region. The map shows the presence of regional clusters with high WUI fractions in some parts of Europe. Around several peri-urban areas high occurrences of WUIs can be observed, for example around Paris, Brussels, but also in the Mediterranean. The Oporto, Madrid and Catalunya regions also show high WUI densities even if the corresponding national

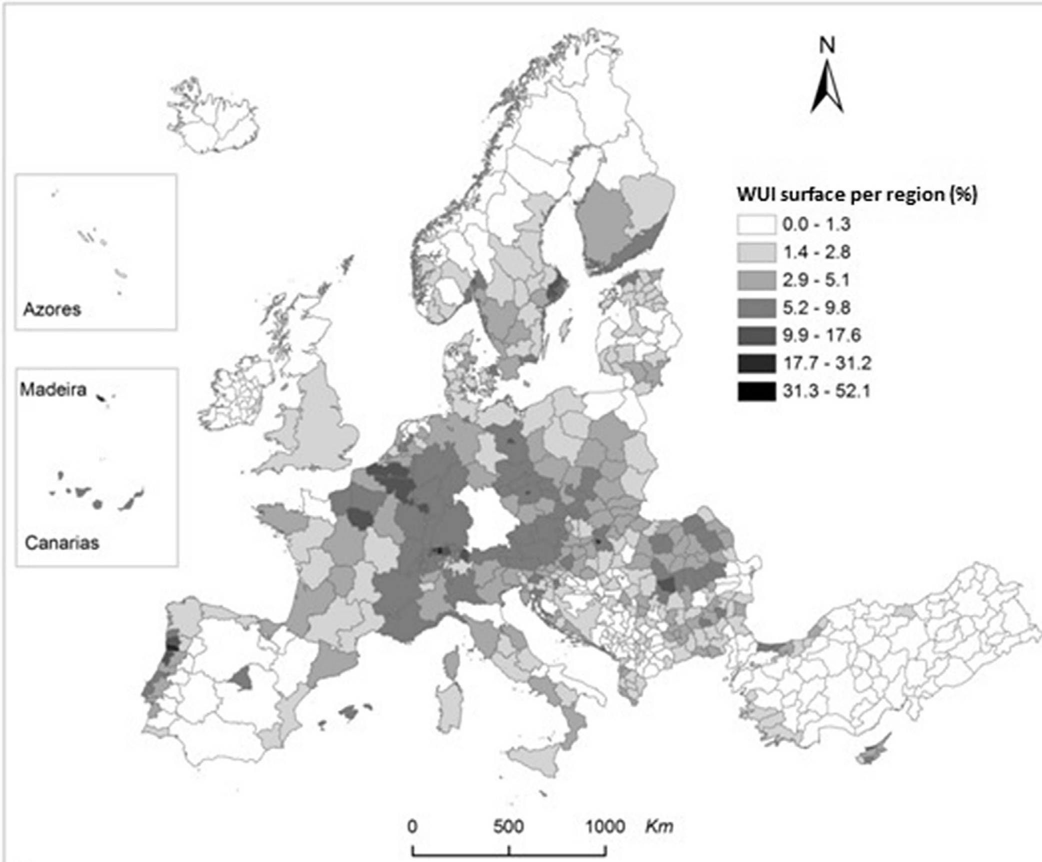

Fig. 7. European WUI surface map at region scale derived from CLC 2006.

percentage WUI is not as high as for France. In Portugal, the area around Oporto coincides with one of the most relevant WUI surfaces. A WUI cluster is also found near the coastline of the Mediterranean basin, around the touristic region like Provence-Alpes-Côte d'Azur and Liguria.

The results in Fig. 7 also show a high WUI distribution in Central Europe, Western Germany, Eastern France, Belgium and Switzerland with more than 10% of WUI surfaces per unit land area. In the Mediterranean region, Cyprus, Portugal and France stand out showing around 4% of WUI surface fraction. The WUI presence is not so high in the Balkan countries. In Eastern Europe, patterns of high WUI areas are found in Romania, where the WUI areas have a clear correlation with the industrial cities (Suditu et al., 2010) and the agricultural decline has produced a high land use vulnerability (Fraser and Stringer, 2009). Also, in Scandinavia the WUI areas is present around the big cities of Oslo, Göteborg, Stockholm and Helsinki. Other regions with a high WUI presence in Poland around Krakow, and in Austria in Graz province. There appears to be a WUI corridor between Prague, Dresden and Berlin. The spatial distribution of the WUI surface at regional scale in Fig. 7 highlights a regional concentration not recognisable from the national summary statistics in Fig. 6.

The two maps in Fig. 8 show the spatial distribution of WUI per area and percent surface covered by large burned areas aggregated at national scale.

3.2. Analysis at cross-national scale

A first visual analysis of the distribution of large fires shows evidence of a strong Mediterranean cluster where large fires occur (Fig. 8b). In order to distinguish the European countries affected by large fires, a LoR model was fitted at cross-national scale, with the centroid points of the large burned areas as the dependent variable and the WUI distance as the explanatory variable. At cross-national scale, the area under the ROC curve was 0.53, moderately significant.

The fitted model of the centroid positions of large burned surfaces as a function of WUI distance in Fig. 9 shows that large fires are more likely near a WUI. The model at cross-national scale shows that LoR is able to estimate the probability of presence/absence of large burned surfaces. The hypothesis of an increasing probability of the occurrence of large near a WUI area, first 10 km, has been confirmed by this model.

3.3. Analysis at national scale

The probability of occurrence of a large burned surface was calculated considering the distance from WUI areas mapped from CLC 2006, as predictor variables. In this next analysis step the LoR was fitted only for those European countries with a presence of enough large fires (national burned surface $\geq$ 0.1%) and a WUI surface $\geq$1%, the selected countries coincide with Mediterranean basin.

The results in Table 3 shows that the occurrence of large fires of >40 ha in size can be explained by the distance from the nearest WUI for most of the countries studied here. The highest predictive capacity is found for Albania with ROC = 0.62 and the lowest for Kosovo with ROC = 0.36.

The hypothesis that the locations of large fires occur more frequently in proximity to a WUI area was confirmed for some

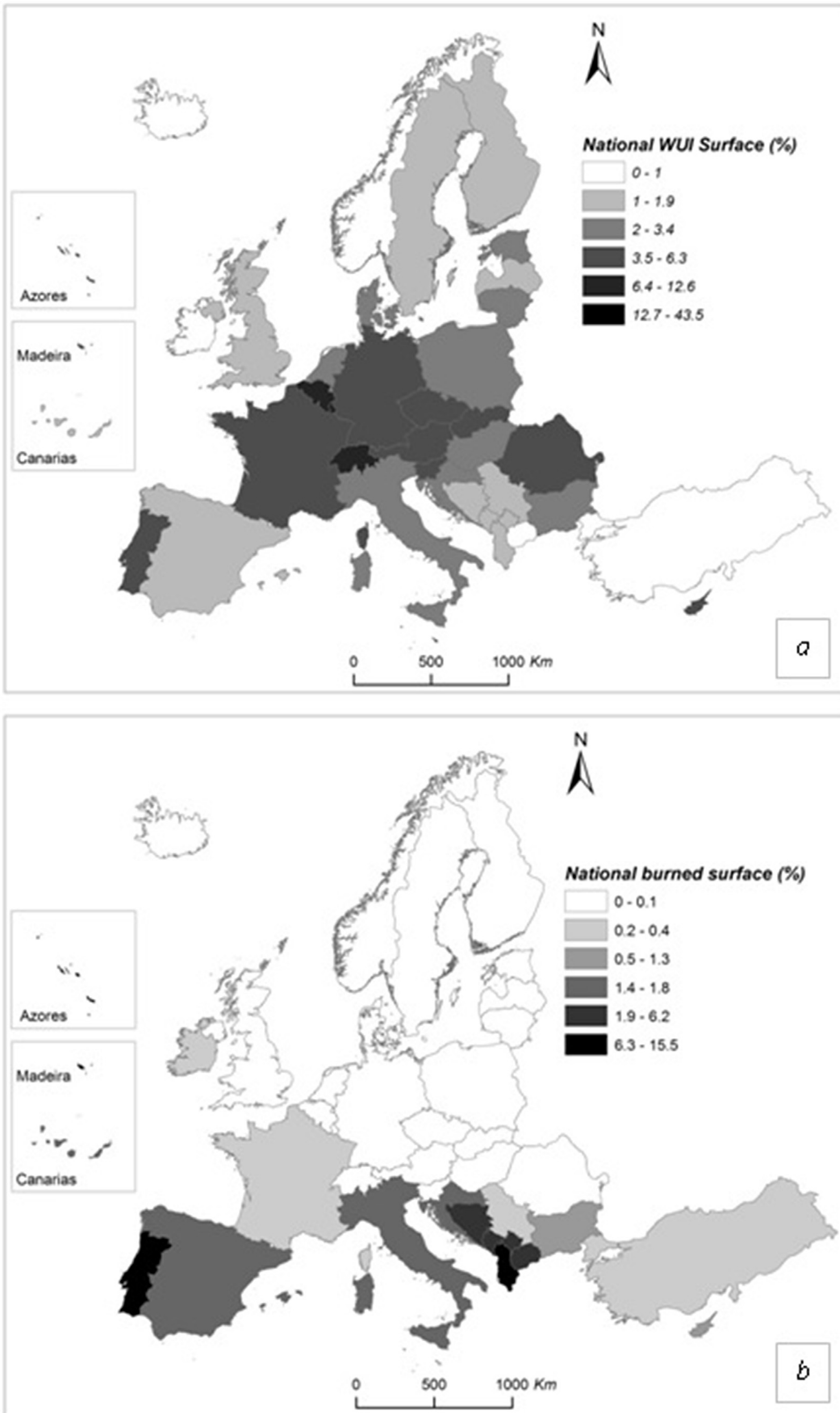

Fig. 8. a) Density of WUIs per unit area at national scale for the NUTS 1 regions; b) Percent of large burned areas at national scale for NUTS 1 regions.

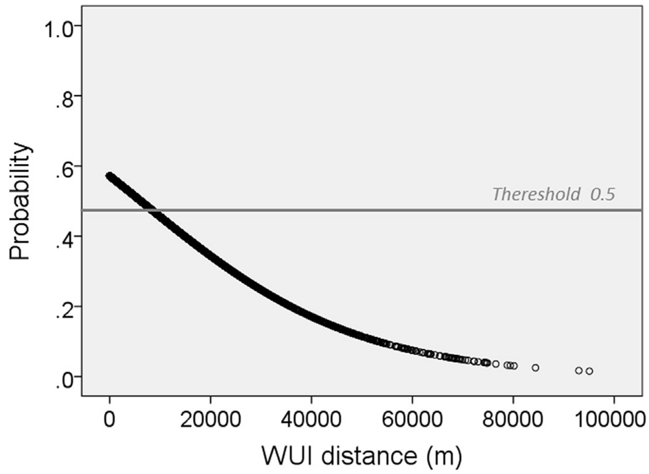

Fig. 9. Probability curves for the occurrence of large burned surfaces over the entire study region as a function of WUI distance.

differences for European countries in their characteristic fire regimes and how they relate to the presence of WUIs.

Fig. 10 shows the estimated probability curves of the occurrences of large burned areas (>40 ha) as a function of the proximity to a WUI for the countries with a strong statistical relationship from Table 3. Albania shows the strongest positive response of the probability of large fires close to a WUI, with a discernible influence of the proximity to a WUI up to a distance of around 5000 m (Fig. 10). Bulgaria, France, Italy, Spain and Cyprus show the same relationship. From Table 3 and Fig. 10, we conclude that at national scale:

(i) Large fires occur more frequently near WUI areas in Albania, Bulgaria, Cyprus, France, Italy and Spain (ROC > 0.5, high probability for low WUI distance);
(ii) No significant relationship between proximity to a WUI and occurrence of large fires was found for the Former Yugoslav Republic of Macedonia (FYROM), Montenegro and Portugal (ROC ≤ 0.5, flat line in Fig. 10);
(iii) Large fires occur slightly less frequently near WUI areas than away from WUI areas in Bosnia and Herzegovina, Croatia and Kosovo, but this is not significant (ROC < 0.5, low probability for low WUI distance).

Table 3
LoR model between European large burned surfaces and WUI distance at national level applied in countries with more than 0.1% of burned surfaces and 1% of WUI surfaces.

Countries	Model behaviour respect WUI distance (regression coefficient)	ROC (burned surface probability)
Albania	Indirect	**0.62**
Bosnia and Herzegovina	Direct	0.45
Bulgaria	Indirect	**0.55**
Croatia	Direct	0.46
Cyprus	Indirect	**0.54**
France	Indirect	**0.57**
Italy	Indirect	**0.60**
Kosovo	Direct	0.36
Montenegro	Direct	0.48
Portugal	Direct	**0.50**
Spain	Indirect	**0.53**

The bold indicate numbers above the significance thereshold (0.5).

countries but not for others. The area under the ROC curve was above the significance threshold of 0.5 for Albania, Bulgaria, Cyprus, France, Italy and Spain (Table 3). For these countries there is a significant relationship between the occurrence of large fires and the proximity to a WUI. For the other countries with ROC <0.5 the relationship is not as strong, although some ROC statistics are very close to 0.5. The LoR analysis has highlighted important regional

European countries can thus be clustered into three distinct groups based on the influence of the presence of WUIs on the occurrence of large fires.

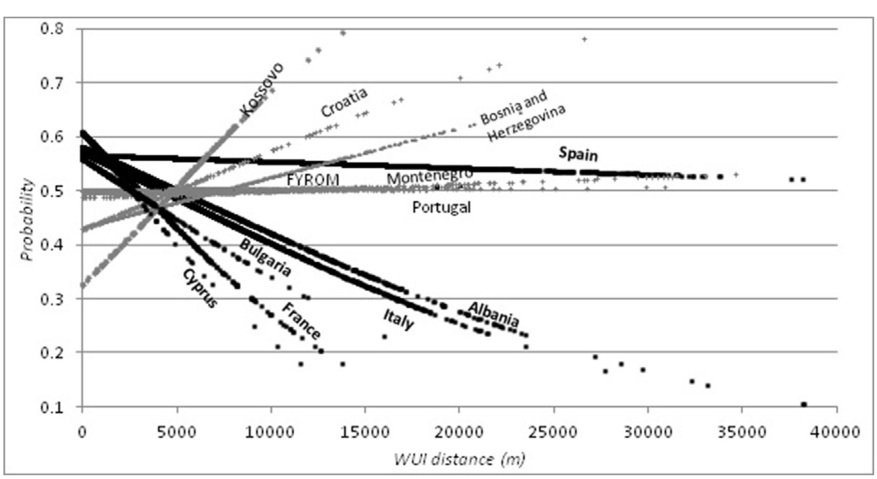

Fig. 10. Burned surface probability as a function of proximity of the nearest WUI by country. Only countries with a statistically significant relationship are shown (ROC > 0.5).

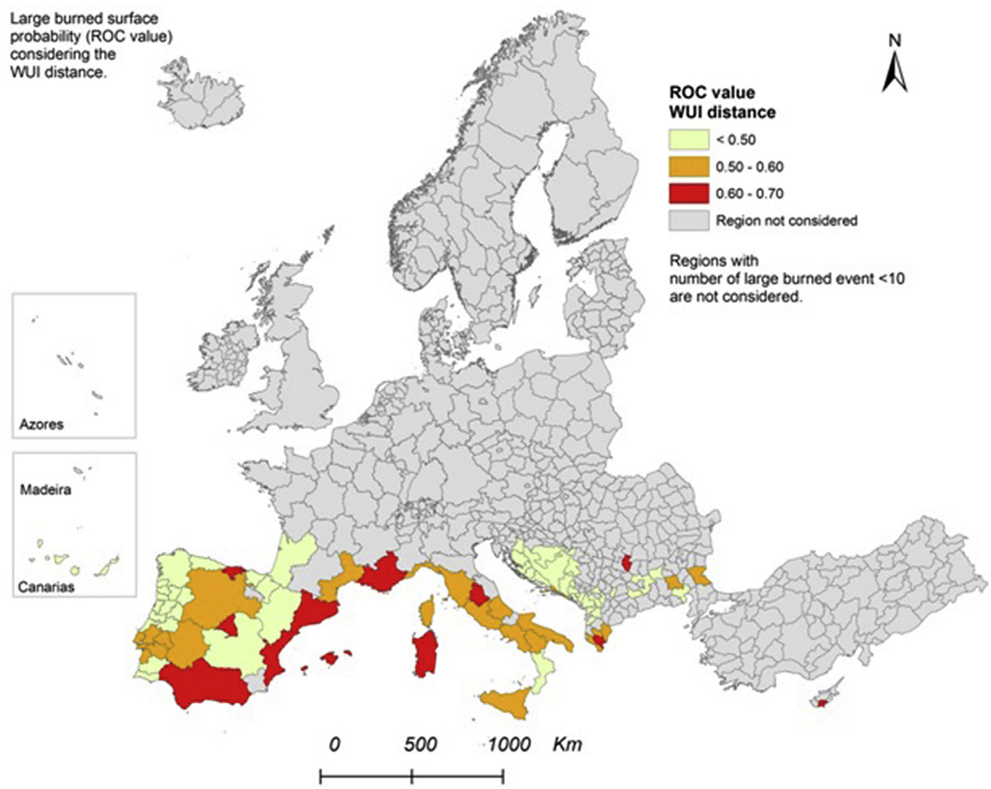

Fig. 11. Map of ROC values from the LoR models of large burned area occurrences as a function of the distance to a WUI at NUTS 2 regional scale in all regions with more than 10 burned surfaces between 2002 and 2013.

3.4. Factors associated with large fire occurrence at regional scale

An analysis at regional scale divided the study area into 82 NUTS 2 regions. Only the regions with more than 10 large burnt areas between 2002 and 2012 were included.

The map of Europe in Fig. 11 shows the strength of association of large burned area occurrences and the distance to the nearest WUI. The map colours correspond to the ROC values from the LoR models at NUTS 2 regional scale (Table 4). Fig. 11 shows that only Southern European regions fall into this category. A striking feature of this result is that the occurrence of large fires is particularly strongly influenced by proximity to a WUI along the Spanish Mediterranean coastline, Sardinia, Provence-Alpes-Côte d'Azur and near large cities like Madrid.

In Fig. 11 is recognizable the effect of multi-scalar approach determine a higher statistic match considering WUI distance at regional level. In Portugal, at national level a relationship of large fires with the distance from the nearest WUI cannot be found, but at regional level some regions show that the probability of large forest fires can be partially explained by the proximity to the WUI areas. This is the case for Lisboa and Portalegre. Spain confirms the hypothesis that urban sprawl around large cities shows WUI areas strongly related with large fires (Madrid and Barcelona). In France, only the Mediterranean regions of Languedoc Roussillon, Corse and Provence-Alpes-Côte d'Azur show significant ROC values. Also in Italy, all the Tyrrhenian regions, with the exception of Calabria, and Umbria, Apulia and Abruzzo, reveal statistical importance of WUI distance.

In the Balkan countries at regional level only the region Dubrovacko-Neretvanska shows a significant ROC value. In Albania, the southern regions of Berat, Gjirokastër and Korçë highlight a hotspot coincidence of large fire events and minimum WUI distance. Other regions with relevant ROC value were identified in Bulgaria, Vidin region, and the Limassol region of Cyprus.

3.5. Probability curve

To compare the behaviour of forest fire probability with respect to WUI distance, some probability curves were elaborated. The probability curves of the countries showing a ROC value >0.5 are shown in Fig. 12. For each of these countries, the probability curves of the NUTS 2 regions with the highest ROC value for the WUI distance are plotted in Fig. 12.

The probability curves generally show an increasing probability of large fire occurrences when close to a WUI. The probability curve analysis in Fig. 12 supports the hypothesis of this study that proximity to the nearest WUI increases the risk of large fires, at least in some European regions. The methodological approach adopted here allows a cartographic representation of those regions where the proximity to a WUI poses a risk factor for catastrophic large fire outbreaks. This approach supports fire risk management strategies and land use planning.

4. Discussion

This study presents the first European map of the extent of WUI areas in order to analyse the risk of large forest fires, which are particularly frequent in the Mediterranean states. To achieve this goal, we present a suggested European-scale definition of the WUI based on the only available harmonised European-scale land cover map, CORINE.

Based on the European scale map of the WUI extent, the occurrence of large burned areas of >40 ha in size is analysed in relation to their proximity to the nearest WUI area, aggregated at

Table 4
LoR models at NUTS 3 regional scale for all regions with at least 10 large fires, >1% of burned area between 2002 and 2013 and >0.1% WUI density. All combined LoR models are significant (ROC > 0.5).

Country	NUTS 2 region	WUI distance
Albania		**0.62**
	Berat	0.58
	Dibër	0.48
	Gjirokastër	0.67
	Korçë	0.57
	Kukës	0.36
	Lezhë	0.41
	Shkodër	0.43
	Tiranë	0.41
	Vlorë	0.53
Bosnia and Herzegovina		**0.45**
	Federation of Bosnia and Herzegovina	0.50
	Republika Srpska	0.38
Bulgaria		**0.55**
	Burgas	0.55
	Haskovo	0.41
	Kyustendil	0.35
	Lovech	0.50
	Sofia	0.50
	Stara Zagora	0.51
	Vidin	0.62
Croatia		**0.46**
	Dubrovacko Neretvanska	0.55
	Karlovacka	0.50
	Licko-Senjska	0.50
	Splitsko-Dalmatinska	0.40
	Sibensko-Kninska	0.50
	Zadarska	0.38
Cyprus		**0.53**
	Limassol	0.63
France		**0.57**
	Aquitanie	0.47
	Corse	0.52
	Provence-Alpes-Côte d'Azur	0.67
	Languedoc Roussillon	0.58
Italy		**0.60**
	Abruzzo	0.55
	Apulia	0.58
	Basilicata	0.57
	Calabria	0.50
	Campania	0.56
	Liguria	0.60
	Lazio	0.54
	Sardinia	0.63
	Sicily	0.53
	Toscana	0.56
	Umbria	0.62
Kossovo		**0.36**
	Gnjilane	0.35
	Pecki	0.24
	Prizren	0.39
Montenegro		**0.48**
	Cetinje	0.48
	Danilovgrad	0.45
	Nikšic	0.42
	Plužine	0.45
	Podgorica	0.50
Portugal		**0.50**
	Aveiro	0.40
	Beja	0.36
	Braga	0.32
	Bragança	0.50
	Castelo Branco	0.50
	Coimbra	0.43
	Evora	0.52
	Faro	0.47
	Guarda	0.44
	Leiria	0.31
	Lisboa	0.56
	Portalegre	0.54
	Porto	0.41
	Santarém	0.55
	Setúbal	0.52

Table 4 (*continued*)

Country	NUTS 2 region	WUI distance
	Viana do Castelo	0.43
	Vila Real	0.47
	Viseu	0.40
Spain		**0.53**
	Andalucia	0.63
	Aragon	0.50
	Cantabria	0.64
	Castilla y Leon	0.59
	Castilla la Mancha	0.50
	Catalunya	0.68
	Comunidad de Madrid	0.65
	Comunidad Foral de Navarra	0.28
	Comunidad Valenciana	0.64
	Extremadura	0.51
	Galicia	0.51
	Islas Baleares	0.63
	Islas Canarias	0.49
	Pais Vasco	0.50
	Principado de Asturias	0.33

country scale. Smaller burned areas near WUIs were brought under control by the disaster response and emergency management services. The analysis of the empirical relationship between large fire occurrence and WUI areas in different countries, where different fire risk management and firefighting capacity and policies are implemented, allows conclusions to be drawn about the risk of wildfires damaging people, economic assets and infrastructure.

The results show a high WUI surface around the peri-urban areas in the majority of large cities of the Mediterranean area. It is well known that fire size distribution depends on ecoclimatic region. For instance, for the circumpolar boreal biome, Lehsten et al. (2014) describe the influence of ecoregions on the fire size distribution.

The LoR model detected statistically significant relationships between fires and WUI distance for some countries, but the sign of the relationship is country-dependent. The Mediterranean countries have very different socio-economic structures, geographical features, land use planning and firefighting policies and procedures. Portugal shows a high number of large burned surfaces together with a high overall extent of WUI surfaces, but the relationship is not strongly significant (ROC = 0.5). In Portugal, the fire regime is characterised by the occurrence of large fire, generating large burned surfaces (San-Miguel-Ayanz et al., 2013b; Marques et al., 2011). In these cases the centroid points of the burned area polygons represent a high level of generalisation of the geographical information that could lead to weak statistical relationships. The extent of the burned surface polygon reaches far beyond its representation by the centroid point in cases of large fire.

In Spain, a moderate but significant influence of the distance from the nearest WUI on large burned surfaces was found. The large fire phenomenon also plays an important role in Spain, especially in Galicia where large fire events occur in the South and East of the region where the presence of eucalyptus and pine facilitate the fire spread (Balsa-Barreiro and Hermosilla, 2013). In the other provinces such as Madrid (Romero-Calcerrada et al., 2008) and Barcelona (Modugno et al., 2008) the large forest fires occur in close proximity of the urban sprawl into forested areas, creating an increased WUI area. At regional level, strong relationships have been found in the areas characterized by abandoned land, land use conflicts, important summer tourist movements, as well as forest fire hotspot areas in proximity of the coastline. These phenomena seem to be related to growing WUI areas, with a high incidences in regions such as Provence-Alpes-Côte Azur (Etienne et al., 1998), Sardinia (Bajocco et al., 2010), or Catalunya (Gonzalez-Olabarria et al., 2012).

The LoR at national scale cannot distinguish between such regional differences in the fire regime, and the overall relationship could appear weaker due to the mixing of regional differences. We observe, at regional level, a general increase of ROC value for the WUI variable respect to the cross-national and national scale.

The results of national LoR model have to be interpreted under consideration of different land cover change trends in Europe. In the Balkans, a direct relationship of burned surface probability with respect to WUI distance was found. In the case of the Balkan countries, the European Environment Agency has described an ‘urban land take’ in the period 2000–2006 (EEA, 2013). Countries like Bosnia and Herzegovina, Croatia, Kosovo, FYROM and Montenegro show a moderate trend of urban growth. Albania is the European country with the highest level of ‘urban land take’. This may explain why national probability curves for large fires related to WUI distance show the strongest functional relationship between minimum WUI distance and large fire occurrence for Albania.

Other factors influence the occurrence of large wildfires, such as climatic oscillations (Balzter et al., 2007), rainfall anomalies and density of human population (Jupp et al., 2006) and regional-scale soil moisture anomalies (Bartsch et al., 2009). However, these factors affect the temporal dynamics of large fires and do not take into account the interactions between people and forest fuel in the WUI as an important factor determining the fire regime.

Forest fire dynamics in South-Eastern Europe are influenced by rapid social economic changes (Goldammer, 2002). Countries such as Bulgaria and Albania experienced a fast transition from centrally planned economies to market economies and forest fire observations show an alarming increase in the last few decades (Goldammer, 2003). The LoR analyses presented here are consistent with this trend, showing strong influences of the WUI on the presence of large fires in these countries, especially around state capital cities.

The LoR models at national scale (NUTS 1) provides a general overview at European level, but the ROC values could be affected by spatial over-generalisation if within-country regional differences lead to spatial heterogeneity. The LoR models at regional level (NUTS 2) highlight regional forest fire dynamics and in general show a high importance of WUI distance. Whether to use NUTS 1 or NUTS 2 regions for this analysis is a choice between more aggregation with a loss of spatial detail, and finer spatial detail at the expense of the sample size within each region polygon (fewer fires

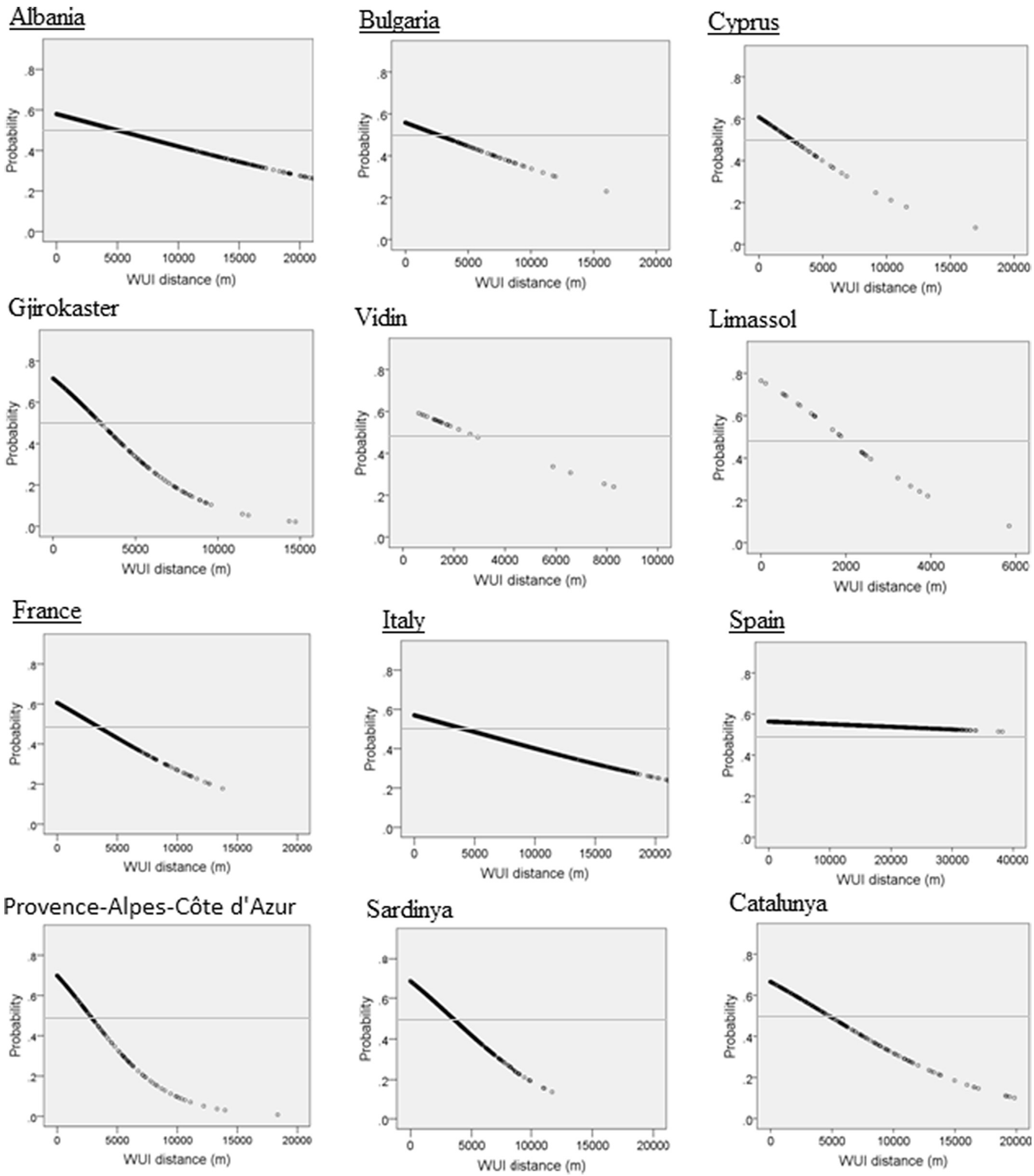

Fig. 12. Probability curve elaborated on the significant regional WUI value.

per unit if smaller units are used). If too few large fires have been detected in a region, the risk of spurious results is high because the relationship with WUI distance is modelled based on too small a sample size.

The present study shows that when using a standardised methodology to map WUI areas at European continental scale, geographically varying relationships between the occurrence of large burned surfaces and their proximity of a WUI area can be found, documented, mapped and quantitatively analysed.

The key finding of this geospatial analysis is that in several Mediterranean countries there is a strong relation between the presence of large burned surfaces and their proximity to WUI areas. This result reinforces the need to better manage the risk of wildfires to infrastructure and people in these countries. WUI mapping provides a very important data product for fire prevention and land use planning with special consideration of forest fire risk.

A multi-functional agriculture has been suggested as a means to control the growth of artificial areas in peri-urban regions while ensuring a sustainable production of rural goods (Zasada, 2011). Such an agricultural policy would help to prevent the direct contact between woodland and urban land and contribute to solving the challenges created by WUIs to fire risk.

5. Conclusions

(i) The presence of WUI areas is a common phenomenon in European countries. Their presence is observed in Central Europe and in most important peri-urban areas confirming trends towards more urban land uses in rural regions and shrub encroachment into the peri-urban environment.

(ii) Large burned surfaces tend to occur more frequently in proximity to WUI areas in many European countries, including Albania, Bulgaria, Cyprus, France, Italy and Spain ($ROC > 0.5$). Their probability of occurrence tends to be highest in a buffer zone of up to 5 km around the nearest WUI.

(iii) The aims, spatial scale, geographical data and conceptual WUI definition are all crucial elements to define a cartographic WUI map. The WUI interaction with large forest fires shows an important regional dimension and the multi-scale approach has been useful to consider the role of WUIs in the management of wildfire risk.

(iv) An influence of the presence of WUI areas on the frequency of large burned surfaces is observed in the Mediterranean countries. However, in some cases such as Portugal and Spain, there are regional within-country differences in the fire regime which lead to a loss of explanatory power of the LoR due to the spatial aggregation at national scale.

This study highlights the important role of wildland/urban interface areas for the occurrence risk of large wildfires in Europe. The WUI has been shown to increase the risk of large fires in some regions of Europe. Here, WUI areas can be interpreted as a failure of regional and local agricultural economic structures and policies, urban planning and forest fire risk management.

The definition of the WUI and its related translation into a cartographic product at European scale is a crucial step towards a European scale approach to the problem of catastrophic wildfires. The boundaries areas around artificial and vegetation zones that defined the WUI was fixed at 200 m and 400 m, respectively. A sensitivity analysis could be apply for a further check of possible relation between the forest fire and human pressure, also from an ecosystem services prospective. According with a landscape ecology perspective, the ecotone between urban areas and wildland areas represented by the WUI underlines the sensitivity of such transition areas where the human pressure and forestlands come in contact.

Wise land management can provide a valuable ecosystem service of fire risk reduction that is currently not explicitly included in ecosystem service valuations. The authors stress the importance of including this ecosystem service in landscape valuations to account for the significant landscape function of reducing the risk of catastrophic large fires.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2016.02.013.

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