Badia i Perpinyà, Anna; Pallarès Barberà, Montserrat; Valldeperas, Natàlia; [et al.]. «Wildfires in the wildland-urban interface in Catalonia : Vulnerability analysis based on land use and land cover change». Science of The Total Environment, Vol. 673 (2019), p. 184-196. DOI 10.1016/j.scitotenv.2019.04.012

1. Introduction

Wildfires have historically been one of the primary forces shaping ecosystems (Bond and Keane, 2017; Greene and Michaletz, 2015). In Mediterranean countries specifically, fire has been used as a management tool to control forestry. Nonetheless, the economic viability of forestry has declined due to the crisis in traditional primary activities that began in the second half of the 20th century. This has caused a change in the structure of forests, the model of urban occupation in a large part of the Mediterranean regions, and the manner of relating to fire. The agroforest mosaic that dominated the landscapes of the Mediterranean basin and the intensely productive relationship between the inhabitants and the environment have been transformed into a landscape polarized at two extremes: on one hand, the extensive urban zone and/or Wildland-Urban Interface (WUI) (USDA 2001; Stewart et al. 2007) where the population resides, and on the other, natural spaces, primarily wooded and often delimited by protective boundaries that have recreational and conservation functions.

The term 'landscape' implies the natural, cultural, and visual elements of an area. In this paper we use 'landscape' to mean "an area […] perceived by people, whose character is the result of the action and interaction of natural and/or human factors" (Council of Europe 2016). The objective of this paper is to determine how WUI vulnerability to wildfires varies by area, depending on the dynamics of land use and land cover change (LULCC), and by the frequency of fire ignition. In this paper, we compare three case studies in Catalonia which have diverse driving forces in terms of LULCC. There is a strong association in Catalonia between the occurrence of large burned areas and distance to the nearest WUI (Modugno et al. 2016). The biophysical aspects of land cover and meteorological properties are not considered in this paper.

The hypotheses of this research are: a) there were LULCCs in the three study areas between 1993 and 2009, b) the factors affecting LULCCs are not the same in each area, and c) LULCCs and different dynamics affect wildfire behaviour in WUI and so vulnerability in the three study areas.

Wildfires in WUI are complex phenomena. As fires are expected to become more severe in the future (Flannigan et al. 2013), studying the structures and relationships between people and WUI that perpetuate this problem is one of the foremost challenges of forest fire management. Several important variables, such as urban sprawl, landscape value, and LULCC, have to be considered in this research (Fig. 1).

Fig. 1. Conceptual Framework

Urban sprawl is defined as the physical expansion of urban areas (Berry 1976; Indovina 1990). Urban sprawl experienced high rates of growth in Europe in the twentieth and twenty-first centuries, , and was especially intense in Mediterranean countries (European Environment Agency, (EEA) 2006). Urban sprawl has modified the earth's surface world-wide. The delimitation of urban sprawl is difficult to quantify in terms of the WUI, specifically because it is conceptualised as an urban development on the margins of the compact city (Henry 2004). For policy reasons, urban sprawl is defined as:

> "the physical pattern of low-density expansion of large urban areas, […] mainly into the surrounding agricultural/rural areas" (EEA 2006).

Urban sprawl lies at the centre of various processes and forces which generate conflicts about how people use the natural landscape (Herrero 2011).

WUI involves a specific type of urban sprawl and, conceptually, relates only to forest areas. It emerged in the United States of America in the 1990s, following growing concern about the proliferation of human settlement in forest areas. The first mention of this new type of increasingly frequent fire, was in California in the 1970s (Butler 1976). In general, the literature refers to a 'wildland urban interface', but the definition can be more specific, using the word 'interface', as the process wherein new homes are built, pressing against the wildland; and the word 'intermix' is also used, to mean single homes or other buildings scattered throughout the wildland area (Davis 1990, Stewart et al. 2007). The most accepted definitions are those proposed by USDA and Stewart:

> "The WUI community exists where humans and their development meet or intermix with wildland fuels" (USDA 2001 p. 752-753).

and

> "The WUI definition always includes three components: human presence, wildland vegetation, and a distance that represents the potential for effects." (Stewart et al. 2007 p. 202).

The WUI concept has been consolidated within the discipline (Vince et al. 2005). WUI comprises two territorial subsystems – wildland/forest and urban areas – and the interactions established between them. WUI typologies are defined according to the following factors: land use, metropolitan and rural area mixture, forest density around WUI, road accessibility, potential progress of fire in the vicinity (both on the borders and inside the settlement), existing options for fire defence, exposure of houses to potential fire within the interface, and level of vulnerability (Myszewski and Kundell 2005; Caballero et al. 2007; Herrero 2011; Galiana-Martin et al. 2011; Badia et al. 2011).

In parallel to processes in the USA, the management of European rural areas have enlarged the wildland urban interface, increasing the risk of forest fires (Viegas, 2009). Institutions and research groups are therefore addressing their concerns to find solutions to this problem (Wildland-Urban Interface Forest Fire Risk Observatory and Interest Group in Europe (WUIWATCH); Wild land-urban Area Fire Risk Management (WARM)); and building decision support systems for fuel management and fire hazard reduction in Mediterranean wildland-urban Interfaces, FIRE STAR (CORDIS, n.d.; Galiana 2012).

Institutionally, the increasing development of WUI areas has been of increasing concern, prompting planning policymakers to preserve landscapes in order to avoid greater impacts on territory and human lives.

The role of landscape is a fundamental consideration in this study: on the one hand, there are biophysical changes to the landscape, and on the other, the value of a landscape as perceived by certain parts of the population. Approaches to the definition of 'landscape' vary within disciplines: from an ecological perspective, it is a mosaic of interacting ecosystems (Forman 1995; Turner 2005); from a wildlife perspective, it is a heterogeneous distribution of habitat (Dunning et al. 1992); for the World Heritage Committee, it is a cultural property that represents the combined works of nature and people, and an expression of the lived history of the population that shapes their surroundings (UNESCO 2008); and for geographers, it involves the physical traits that configure land cover, and also has a subjective element related to the experiences, feelings and emotions that individuals or society might have in relation to it (Bertrand and Bertrand 2006; Nogué 2007).

The concept of landscape units is a central point in this research. It helps us to define these areas with the set of landscape characteristics which is relevant to the way a fire is initiate and propagate. According Landscape Observatory of Catalonia, landscape units are:

> "Portion of territory characterised by a specific combination of landscape components of an environmental, cultural, perceptive and symbolic nature and with clearly recognisable dynamics which result in an individuality differentiated from the rest of the territory."

In comparison with politico-administrative borders and municipal boundaries, landscape units allow a better understanding of the characteristics and outcomes of a given territory.

In the first quarter of the twenty-first century, the decreasing use of land for crops, livestock, and forestry represented the beginnings of a structural change in the landscape. The abandonment of farm fields and pastures, and the replacement of combustible vegetation with fossil fuels in buildings and vehicles, for example, have increased the forested area, which became a continuous mass of unmanaged fuels (Vélez 2000; Lasanta et al. 2005, 2006; Badia et al. 2010). Forest mass increased in zones that were traditionally occupied by farm fields, pastures, or lightly-wooded areas; and urban sprawl expanded into the forest areas. Both processes produced a landscape where the boundaries between urban and forested areas are unclear. The binomial relationship between society and nature in the rural context in which the forest environment was a means of subsistence (Cussó et al. 2006), disappeared; and so the land cover linked to traditional primary activities was lost.

The socio-economic value of the landscape has thus also evolved, changing the population’s perception and appreciation of landscapes. On the one hand, the idealisation of nature by the urban population impelled their desire to use forest land to build their houses, and in turn to enjoy the aesthetic elements of living in a ‘natural’ environment. On the other hand, the increasing demand for second homes in Mediterranean settings has increased the necessity of living in forested areas, which at the same time pushed up the prices of land, mainly around mountains that are suitable for skiing. These two factors present a paradox in which forest views are appreciated by the people who buy houses, but where building these houses simultaneously diminishes the aesthetics of the forest and the value of woods. This, in turn, lowers the price of land and raises concerns about forest preservation (Otero et al. 2013; Farina 1991; Agnoletti 2006).

Land use is recorded in the environment, showing how populations use land. The process of how and why land uses change is the most important factor in environmental transformation, particularly in Mediterranean areas with dense populations and intense human activity. Land cover indicates the biophysical land type, while land use change creates land cover changes as a combination of social and environmental factors (Sala et al. 2000; Boada and Saurí 2002; Turner et al. 2007).

'Forest transition' (FT) (Mather, 1992; Rudel et al. 2005; 2010) provides useful insights explaining the historical relationship between forests and society. According to FT, while the worldwide total area of forest cover continues to decrease, the total area of agricultural and livestock cover increases. Conversely, from the second half of the twentieth century, forest land cover actually increased in Western Europe, some parts of the USA, and in some places in Southeast Asia. This change brought with it a series of territorial conflicts that had never previously been experienced in these areas. The historical transformation of forest cover means that the landscape is the result of the use, disuse, or abuse of land by different cultures and societies that inhabit an area. To understand landscape dynamics, LULCC must be analysed, mostly, in terms of WUI vulnerability.

An area's vulnerability refers to its susceptibility to physical harm or damage; and its resilience refers to its capacity for recovery (Miller et al. 2010; Turner, 2010). The vulnerability of a forest area to fire involves its capacity to resist fire ignition, and a fire's subsequent advance. There are areas that are more vulnerable to the development of forest fires than others. There are multiple causes of forest fire vulnerability, the most important being the structure and composition of the landscape, the population density or frequency of human use, and previous occurrences of fire in the area (Cortnet et al. 1990; Radeloff et al. 2005; Theobald and Romme 2007; Caballero et al. 2007; Badia and Pallares-Barbera 2006; Badia et al. 2011). Due to the complexity of WUI composition, WUI vulnerability is higher than in other landscapes and addressing this vulnerability thus requires a combination of resource management and the involvement of diverse agents (Antrop 2004; Lasanta et al. 2005; 2006).

Fire risk management, including implementing civil protection and fire prevention, is more effective than responding to, and extinguishing, a fire when it occurs (Plana 2011; Miller et al. 2010; Turner II 2010). The analysis of land use and land cover, population demands, social perceptions, and the lifestyles of residents is important to prevent ignitions in WUI.

2. Methodology and Data Sources

For this paper, we chose to identify and classify three areas of analysis in order to associate vulnerability with each one. We then defined and studied how the differences in LULCC and the frequency in fire ignitions affected each area. This was done in order to prioritise vulnerabilities in relation to the characteristics of each area, and to provide an assessment using the correct and necessary knowledge to understand the threats to each environment and react appropriately.

Methodologically, this study involved three phases: identifying the most important factors defining the study areas; analysing LULCC from 1993 to 2009 based on the Kappa index and rate of change; and finally, establishing the relevant fire ignition factors for the period 1995 to 2010.

2.1. Identification of Three Landscapes as Study Areas

To establish the three case study boundaries, we first examined four forest fires in WUI zones in Catalonia in 2003 and 2012: two large fire zones and two less extensive ones (Fig. 3). The two large fires, in 2003 and 2012, had strong social and media repercussions, especially because of the loss of human lives and the impact on WUI zones. The other two fires occurred in 2012 in the Catalan Pyrenees.

One of the factors considered when choosing the study areas was the need for diverse scenarios with which to perform the analysis. Diversity is affected by location relative to urban agglomeration. The 'Metropolitan Area' located in Sant Llorenç Savall, where a fire occurred in 2003, is located within the Barcelona Metropolitan Region. It consists of urban sprawl in a forest area (Badia et al. 2010). The 'Agroforest Area' in Alt Empordà county, where a fire took place in 2012, is 160 km north-east of Barcelona. This area consists of a mosaic landscape composed of urban, agricultural and forest areas. The 'Mountain Agrosilvopastoral Area', located in the Pyrenean mountain zone, 250 km from Barcelona (Northern Catalonia), where two fires occurred in 2012, is an urban nucleus in direct contact with pasture and forest zones (Caballero et al. 2007) (Fig. 3).

Because wildfires cross politico-administrative borders, we used the group of landscape units which were affected by fires as a perimeter for each case. In this paper, a landscape unit is a homogeneous area beyond administrative boundaries, with biophysical variables (land use, terrain morphology), historical dimensions to the landscape, visibility analysis, and population perception and sense of place (Observatori del Paisatge 2015; Council of Europe, 2016).

2.2. Land Use and Land Cover Changes, 1993 to 2009

The analysis of LULCC is important in evaluating the vulnerability of landscapes. Some studies use this to quantify annual changes in landscape properties in order to understand how each of these processes affects landscape structure and to better understand and manage the complex interactions between fire and land use (Viedma, et al. 2006; Butsic et al. 2015). High-resolution maps of land cover in Catalonia, taken from the Land Cover Map of Catalonia made by the Centre for Ecological Research and Forestry Applications (CREAF), helped in the analysis of landscape dynamics for 1993 and 2009, using GIS ArcGis (ESRI 2016) and MiraMon (CREAF 2010, 2016). The 16 year period analysed showed very important changes in land use and land cover dynamics in the three study areas.

Methodologically, the LULCC dynamic included the following steps: a) downloading the relevant pages of georeferenced 1993 and 2009 maps, showing the landscape units affected by the selected fires; b) constructing a mosaic of these pages to show the study areas in 1993 and 2009; c) trimming the mosaics to match the study boundaries; d) reclassifying the 241 land cover categories provided in the 2009 map legend, and aligning them with the 22 categories detailed in 1993; e) conducting a second reclassification for both years to facilitate spatial analysis, and further simplification of the 22 categories to seven typologies: densely-wooded, lightly-wooded, scrub vegetation, meadows and grassland, farm fields, urbanised zones, and other; and f) superimposing the reclassified 1993 spaces onto the reclassified 2009 spaces in order to generate a map of the changes that took place, together with tables showing the relationships between them (Fig. 2A).

Fig. 2. Geoprocessing tools used to obtain LULCC maps and statistics. MA example.

The land cover change map (1993-2009, obtained from 22 categories superimposing maps) and the occurrence map (1995-2010) were overlaid to analyse the fire ignitions according to land cover change in the case studies. Finally, the coordinates of fire point occurrences (1995-2010) and fire perimeters (1987-2012) were plotted (Generalitat de Catalunya) to define the case study perimeters.

We used the Kappa index (Cohen 1960) for map comparison purposes to evaluate its accuracy (Ahmed 2011; Yin et al. 2011 Kitada et al. 2012; Nguyen et al. 2018):

$$k = \frac{P_0 - P_e}{1 - P_e}$$

Where,

P_0 = is the relative observed agreement among raters

P_e = is the hypothetical probability of chance agreement, using the observed data to calculate the probabilities of each observer randomly seeing each category.

If the raters are in complete agreement, then $k = 1$; if the observed proportion correct is greater than the expected proportion correct due to chance, then Kappa > 0; and if the observed proportion correct is equal to the expected proportion correct due to chance, then Kappa = 0 (Ahmed et al. 2013).

We used the *P* Rate of Change (FAO, 1996; Echeverría et al. 2006) to analyse the transition of land uses between 1993 and 2009; when the value of P is negative, the land use areas diminish.

$$P = \frac{100}{t_2 - t_1} 1n \frac{S_2}{S_1}$$

Where,

P = rate of change, expressed in %

S_1, S_2 = land use in different time periods

t_1, t_2 = time periods

3. Study Areas

The WUIs studied are approximately 200 km apart, with diverging characteristics. The largest area, the Mountain Agrosilvopastoral Area (MAA) (167,944.8 ha), has a natural protected area (NPA) which is 39.1% of the total area. The Metropolitan Area (MA) (78,405.7 ha) has an NPA, which comprises 35.1% of the total area; and the Agroforest Area (AA) (56,756.1 ha) has an NPA which is 31.4% of the total area (Table 1).

MAA has the highest altitude, with peaks up to 2,883 m; while MA and AA have peaks up to 1,440 m. Temperature and average annual rainfall vary, with MAA having max. 13.4º and min. 2.9º, 1026 mm; while MA and AA respectively have a max. 19.2º, 9.3º, 749.4 mm and a min. 17.7º, 7.3º, 723.7 mm. Wind speed is significantly higher in the AA than in the other two study areas.

Fig. 3. Study Areas. Source: Author.

Table 1. Summary of the Territorial characteristics of the Three Study Areas

The MAA is formed of four landscape units, and fires burned 9,908.7 ha (5.9% of the total area). The MA is formed of three landscape units and the burned area was 5,331.6 ha (6.8% of the total area). The AA has four landscape units, and the burned area was 6,697.2 ha (11.8% of the total area). MA and AA have the highest-density urban areas and the two larger fires. The MAA had the two least-extensive fires.

3.1. The Metropolitan Area, Sant Llorenç Savall

The MA is highly forested, and its altitude increases from 88 m to 1,100 m. There are major rock walls and cliffs, abundant vegetation (especially in crevices), and numerous springs in the highest parts of the mountain. The population is distributed across small villages in the valley, with traditional country houses (the Catalan *masia*) dispersed throughout the territory at altitudes of between 500 m to 800 m, some of which are still active agricultural sites. The rock walls contrast with the densely-wooded and rocky areas, and with the small farms surrounded by woods. The northern part of the MA is flat compared to the rest, with excavated valley floors and a continental climate, which is characterised by warm summers, cold winters, and relatively low precipitation. Most of the agricultural surface is concentrated. *Pinus mugo*, *Pinus halepensis*, and *Quercus* groves coexist with farm fields. The richness of natural (flora and fauna) and heritage (elements of the rural past) landscapes are a public attraction, and they provide a recreational space for visitors to the Sant Llorenç Natural Park, an excellent example of a metropolitan park (Fig. 4).

The 1956 orthophoto map (Fig. 4a) contains evidence of the rural past, with a population nucleus (centre, right) surrounded by fields and extensive lightly-wooded terrain, reflecting the activity that took place in this zone (Fig. 4). A comparison of Figures 4a and 4b (the 2010 orthophoto) reveals a major decline in the agricultural and forest matrix in 2010. Farm fields decreased, and urban cover increased and intruded into a highly-flammable wooded area containing a large quantity of combustible material.

Fig. 4. Metropolitan Area (MA), 1956 and 2010 Orthophotos. Source: Institut Cartogràfic i Geològic de Catalunya (ICC), www.icc.cat

3.2. The Agroforest Area, Alt Empordà

The AA is characterised by lower altitudes (from 0 to 1,440 m) with small rivers and an extensive forest mass covering the northeast (*Quercus suber*) and southeast (*Pinus halepensis*). The mosaic is formed of forest masses of *Quercus suber*, some zones with Mediterranean crops (grapes, olives, and wheat), and others with extensive vineyards that are located between the mountainous zone and the agricultural plain of the county of Alt Empordà. High-speed railways, major highways (A-2 and AP-7), and the underground high-voltage power line provide an infrastructure corridor that determines the character of this territory, splitting it from north to south and affecting its ecological connectivity (Fig. 5).

Despite a major decline in farm fields since 1956, agricultural crops were still part of the AA in 2010. A large part of the agricultural land observed in 1956 was occupied by forest cover in 2010 and, to a lesser extent, by urban cover.

Fig. 5. Agroforest Area (AA), 1956 and 2010 Orthophotos. Source: Institut Cartogràfic i Geològic de Catalunya (ICC). www.icc.cat

3.3. The Mountain Agrosilvopastoral Area, the Catalan Pyrenees

In the valleys at the base of the Pyrenees, single scattered houses are located amidst pastures and small wooded areas. Villages are perched high on rocky promontories, with their fields on the plateaus. In the northern part, there is a large surface area of meadows and grassland. The rest of the area is predominantly wooded, and the matrix structure is fragmented and localised. There are very small rivers, very little evidence of human presence, and some valleys where vegetation has grown quickly after major demographic abandonment. A Romanesque architectural heritage and the seasonal colour changes attract seasonal tourism and second home ownership.

The most important change in the MAA during the period studied was the increasing density of forest cover associated with the progressive abandonment of traditional primary activities, which have declined since 1956, but remain active (Fig. 6). The matrix, formed of woods, meadows and pastures, and farm fields, remains visible, with a structure that is clearly differentiated from the other two study areas. The process of urban sprawl has not been as intense as in the other two areas, although the more recent major wildfires have begun to represent a new threat to these population centres.

Fig. 6. Mountain Agrosilvopastoral Area (MAA), 1956 and 2010 Orthophotos. Source: Institut Cartogràfic i Geològic de Catalunya (ICC), www.icc.cat.

4. Territorial Typologies Based on the Integrated Matrix Model of the Mid-twentieth Century

It seems vital to maintain the original matrix pattern to reduce or extinguish the intensity of wildfires, and to preserve biodiversity and the ecological connectivity of natural spaces. Analysing the different natures of wildfires helps to find their different matrix patterns, which we called Model 1 (for MA), Model 2 (for AA), and Model 3 (for MAA) (Fig. 7; Fig. 8).

Model 1 is characterised by urban sprawl within areas of forest cover, exemplifying the serious problem faced by most WUI zones. We should point out the high proliferation of spontaneous housing urbanisation in Catalonia during the 1960s and 1970s (Muñoz 2004), particularly in the MA. Model 2 represents the areas where the agroforest matrix has been maintained, adding new dynamics such as crop intensification and specialisation, urban sprawl (less intense than in Model 1), the abandonment of spaces originally used for extensive livestock and densification of the forest mass. In Model 3, a denser and less-managed forest cover takes over pasture.

Fig. 7. Diagram of the Current Territorial Typologies, Based on the Integrated Matrix Model of the Mid-twentieth Century.

Fig. 8. Territorial Diagram of WUI Zones in the Three Study Areas.

5. Results and Discussion

5.1. Analysis of Land Use and Land Cover Change, 1993 to 2009

Although the most important land use changes began in 1950, the first available LULCC map is for 1993, and the last one is for 2009 (done by CREAF). LULCC changes in this 16-year period, as shown on the maps, provide evidence of the diverse fire-impact dynamics in the three study areas, in absolute values (Figs. 9, 10 and 11 and Table 2).

Table 2. Changes from 1993 to 2009 in the Three Study Areas

Fig 9. Land Use Land Cover, 1993 and 2009 in MA. Self-produced

Fig 10. Land Use Land Cover, 1993 and 2009 in AA. Self-produced

Fig 11. Land Use Land Cover, 1993 and 2009 in MA. Self-produced

Table 3. Matrix Changes, 1993-2009, Metropolitan Area

LULCC in MA LULC was significant (*k*=0.3 and variance = 4.60305e-10). Forest cover increased, although densely-wooded land cover decreased greatly (-715.6 ha) because of the surface area burned in 2003 (Table 2 and Table 3). The rest of the forest cover – lightly-wooded, scrub vegetation, and grassy meadows – increased, the latter (at 1506.3 hectares) more than the other two. The agricultural surface area was greatly diminished (-2899.0 ha), and gave way to increases in densely-wooded (1069.5 ha), scrub (859.9 ha), and meadows and grassland (740.8 ha) cover. The urban zones increased by 1227.2 ha, occupying 99.2 ha of densely-wooded areas. This apparent anomaly could be due to the photointerpretation of the 2009 images, in which the forest covers part of the urban area, and was attributed to the densification of forest cover. Although an error in the original photointerpretation cannot be ruled out, further exploration is beyond the scope of this work.

Table 4. Change Matrix, 1993-2009, Agroforest Area

LULCC in AA was significant (k=0.3 and variance = 3.63991e-10). The forested surface area experienced the largest growth (Table 2 and Table 4). There was a decline in scrub cover (-1308.4 ha), which became occupied by dense woods, but there were increases in lightly-wooded (1952.7 ha) and meadow and grassland (80.2 ha) cover. We must highlight the decline in farm fields (-2414.8 ha), which was the greatest change: fields gave way to increases in scrub vegetation (853.5 ha) and dense woods (817.2 ha). Urban zones grew (364.7 ha), occupying land previously included in the other (23.4 ha) and farm fields (20.0 ha) categories, which tends to be the flattest, and therefore easiest to urbanise.

Table 5. Change Matrix, 1993-2009, Mountain Agrosilvopastoral Area

LULCC in MAA was significant (*k*=0.3 and variance = 1.75276e-10). Dense woods and clearings increased, and there were decreases in scrub vegetation (-3837.0 ha) and meadows and grassland (-4307 ha) (Table 2 and Table 5). Scrub yielded to dense woods (8252.4 ha), while meadows and grassland were overtaken by scrub vegetation (6826.2 ha), the logical FT succession pattern. Farm fields decreased (-4943.0 ha), and these spaces were occupied by scrub vegetation (2183.8 ha), meadows and grassland (1874.5 ha), and dense woods (1523.0 ha). Urban cover also increased (144.8 ha), although proportionally much less than in the other study areas, occupying previous farm fields (19.4 ha) and scrub vegetation (18.3 ha).

The importance of the transition of land uses, and the differences among the areas, could be perceived in the P-value rates of change (Fig. 11). The results indicate that the three areas experienced an increase in lightly-wooded, urbanised zones, and a decrease in farm fields. There are very large differences between the areas, in terms of meadows and grassland. There are no major differences in the rest of variables.

Tendencies towards urban sprawl and forest transition are reflected in these results. Meadows and grasslands help us to interpret the forest transition process. Meadows and grasslands in MA increased to the detriment of farm fields and densely-wooded areas (Table 3). In AA, this increase was slightly greater, but there was a decrease in the MAA.

This is related to the characteristics of these areas. AA maintains the agroforestry mosaic: even though it was this area that lost most farm fields, it still has more surface with this type of use. The abandonment of agricultural and livestock activities in the MAA implies that there was an increase in meadows and grasslands in this area.

Fig. 12. Rate of Change Comparison for the Three Study Areas

To summarise, forest and urban covers increased in all three cases, and farm fields were abandoned. In the MA, forest areas increased along with a clear decrease in cultivated fields, which both became occupied by urban cover. The AA was characterised by a marked decline in agricultural terrain, which gave way to scrub vegetation. In the MAA, there was an increase in forest cover, offset by the loss of scrub vegetation, meadows and grassland (Fig. 12).

In the MA, the most important change was the loss of agricultural and forestry activity, and the growth of urban sprawl in direct contact with the forest environment. This dynamic explains the current problem with wildfires in these zones. Although there is much less urban pressure, the dynamics of the AA are quite similar to the MA. Persistent agricultural activity in the AA is one of the most significant differences between them, and explains the persistence of the matrix. Finally, the MAA has preserved the largest amount of agricultural, forestry, and livestock activity of the three areas, although it is much less than it was 60 years earlier. Urban sprawl is practically non-existent, although some new housing has been built for seasonal visitors attracted by the natural values of these surroundings.

5.2 Incidence of Wildfires

The incidence of wildfires provides an estimate of the fire regimen and extension throughout the territory studied here, in terms of the number of fires started, the area burned, and the percentage of the area's total surface area that was burned. The MA had the highest number of fires, and also the largest surface area burned. In the AA, fewer fires burned a larger surface area. Finally, the lowest number of fires and lowest percentage of burned area (half that of the AA) were in the MAA (Table 6, Fig. 13).

Table 6. Surface Area and Number of Fires by Landscape Typology (1995-2010 data)

Fig. 13 Ignition Points in the Three Study Areas (1995-2010). Self-produced

We studied the dynamics of forest fire from LULCC maps (1993-2009) and fire ignition points (1995-2010) to assess the changing trends (Table 7). In the MA, nearly half (169) the 344 fires that occurred between 1995 and 2010 started where forest cover remained. These 169 fires burned 4269.8 ha (80% of the total burned surface area). In the AA, 19 fires in scrub vegetation (in 1993) gave way to dense woods (in 2009) and burned 5910.58 ha (89% of the total burned area). Finally, in the MAA, 56 fires were started in densely-wooded areas (unchanged) (16% of the total burned surface area), 23 in scrub (unchanged) (43% of the total burned surface area) and 20 in farm fields. A comparison of the 424.1 ha of this surface area that was burned in zones where scrub vegetation remained in MAA, with the 64.2 ha that burned in the AA and 41.6 ha in MA, shows that a very similar number of fires (19 in MAA, 23 in AA, and 16 in MA) burned nearly ten times as much surface area in the MAA than in the AA and MA. Forest continuity and a greater efficiency in extinguishing fires in the MA and MAA may explain this difference, however, in MA, 80% of the surface burned was densely-wooded land and, in AA, 89% of surface burned was scrub (in 1993), giving way to densely-wooded land (in 2009).

The ‘extinction paradox,’ whereby burning a smaller area today means more fuel and larger or more intense wildfires tomorrow (Otero et al. 2017), seems to explain these results. That is, the fire response system managed to extinguish 98% of the fires in Catalonia, but the resulting fuel build-up increased fire severity, such that the remaining 2% comprised 90% of the burned surface area (Costa et al. 2011). In addition, the tramontane wind that is so typical of this zone can also play a key role in spreading fires. This factor was not included in our analysis because of a lack of access to the specific meteorological data needed, and is therefore not the subject in our research.

By way of contrast, the traditional use of controlled burns provided an effective means of fire control, and could be used either as a preventive or as a firefighting measure. In the prevention phase, controlled burning helps to reduce the combustible plant fuel in forest terrain, and affects the behaviour of any eventual forest fire, helping to keep it within the bounds of the capacity of the firefighting services. Fires are caused by fuel, not by the spark itself (Minnich 1987). Along the same lines, Davis (1995) insists that prescribed burning is the most effective technique for reducing the accumulation of combustible fuel.

Table 7. Number of Fires (1995-2010) and Changes in Land Use* (1993-2009) in each Study Area. *This table synthesises the fire impact for each change involving burned surface areas.

In the MA, forest fires occurred exclusively where there were changes in forest cover. In contrast, the ignition points for AA and MAA fires included changes in land use related to farm fields, reflecting the greater heterogeneity of the landscape. Of the metropolitan fires recorded, most originated in densely-wooded land cover, reflecting the serious structural problem this presents with respect to WUI zones intruding into wooded areas.

In the MAA, the greatest number of burned hectares corresponds to fires where scrub cover remained, which could be related to the higher frequency of fires in pastures. In contrast to the other two study areas, MAA fires were sometimes started where there was agricultural land cover, a finding that would justify a greater use of fire as an agricultural land management tool, again with reference to the aforementioned 'extinction paradox'. In general, the fires that burned the largest surface area affected zones where forest cover had been maintained, clearly demonstrating the correlation between FT and a greater impact when forest fires occur.

6. Conclusions

Our research validates previously formulated hypotheses: a) based on Kappa index (0.3) we can confirm there are LULCC in the three study areas, but b) changes take different forms in these three study areas that can be explained by rate of change, and c) because the behaviour of wildfires in WUI follows different dynamics, it affects vulnerability differently in the three study areas.

The results of the study and the impact of the fires in each of the three typologies, showed that all three study areas shared a trait: the abandonment of traditional activities negatively affected WUI vulnerability. The economic and social context of each study area generated different territorial dynamics for each typology. These can be summarised into four major categories: a) changes in the structure of the landscape, b) WUI characteristics, c) impact of the fires in the different WUI zones, and d) fire vulnerability.

a) Changes in land use and land cover: The MA typology is characterised by a strong forest component, with a proliferation of primary residences inside the wooded area. The AA maintains mosaic zones that make it optimal for the prevention of wildfires, as they break up the forest continuity. On the more marginal agricultural land, there is a process of forest and urban densification, and a lack of management in *Quercus suber* and *Pinus halepensis* forests, that have repercussions for fire intensity. Finally, in the MAA, the changes also trend toward FT because of the abandonment of farm fields, pastures, and forestry activity. Nonetheless, the pace and intensity of change were greater in the first two study areas. The analysis of LULCC revealed differences in dynamics and intensities, even though all three study areas showed evidence of FT effects.

b) WUI characteristics: The MA is characterised by a greater consolidation of WUI zones in direct contact with forest continuity. In the AA, WUI zones were noted to be in direct contact with continuous forest mass or surrounded by an agroforest matrix.

In the MAA, urban centres are traditionally framed by pastures or farm fields, but showed the effects of normal FT-related LULCC.

c) Fire impact: Although there are many other factors conditioning the occurrence of fires and the burned area dimension than only the ones used in this study, we can say that, the MA and AA had the most fires, the largest burned surface area of the three areas studied, and the largest expanse of WUI zones. According to the territorial characteristics, we would expect the AA to benefit from its mosaic because fires are not as easily propagated, however, there was a higher number of burned hectares than in the MA, where there is more forest continuity. This mosaic should be strengthened to reduce the availability of fuel and to limit the effects of large wildfires. Finally, even though there were no large forest fires in the MAA during the years studied, more recent fires provide evidence of the growing vulnerability of these zones, due to the disappearance of the MAA matrix.

d) Vulnerability in WUI zones: The fire vulnerability of WUI zones is the distinctive trait of the MA, given its characteristics and dynamics related to the density of wooded areas and WUI density. In the AA, the location of WUI in marginal zones in direct contact with forest cover highlights the vulnerability to which these settlements are exposed. In the mountain MAA, the WUI zone is smaller than in the other two typologies, however, similar dynamics were noted, that could be the source of future problems related to wildfires, and that provide evidence of growing vulnerability in environments where wildfires traditionally did not occur.

This study contributes knowledge that complements the available planning and management tools used for preventing wildfires. The present study took a mostly quantitative approach, which was essential to developing an appropriate description and typology of these different landscapes. To support the development of a more complete view of the current WUI situation, future work will involve: analysis of LiDAR data to improve forest management and to analyse the evolution of forest structure, analysis of the spectral indices from satellite imagery (Landsat and Sentinel) to understand urban and forest evolution, study of the synoptic conditions (meteorological conditions), and also qualitative research using oral interviews.

Acknowledgments

This research has been carried out under the projects: Secretaría de Estado de Investigación, Desarrollo e Innovación (CSO2015-65257-R). Secretaría de Estado de Investigación, Desarrollo e Innovación (CS02016-74888-C4-2-R). Agència de Gestió d'Ajuts Universitaris i de Recerca (AGAUR-2014 SGR-1090).

References:

Agnoletti, M., 2006. The conservation of cultural landscapes. Wallingford: CABI

Ahmed, B., 2011. Modelling spatio-temporal urban land cover growth dynamics using remote sensing and GIS techniques: A case study of Khulna City. Journal of Bangladesh Institute of Planners, 4:16-33.

Ahmed, B., Ahmed, R., Zhu, X., 2013. Evaluation of model validation techniques in land cover dynamics. ISPRS International Journal of Geo-Information, 2, 577-597. http://doi.org/10.3390/ijgi2030577.

Antrop, A., 2004. Landscape change and the urbanization process in Europe. Landscape and Urban Planning, 67, 9-26. https://doi.org/10.1016/S0169-2046(03)00026-4.

Badia, A., Estany, G., Otero, I., Boada, M., 2010. Estudio del crecimiento urbano disperso y cambios en el paisaje en Matadepera (Región Metropolitana de Barcelona). Boletín de la Asociación de Geógrafos Españoles, 54, 301-321.

Badia, A., Pallares-Barbera, M., 2006. Spatial distribution of ignitions in Mediterranean periurban and rural areas: The case of Catalonia. International Journal of Wildland Fire. 15, 187-196. http://dx.doi.org/10.1071/WF04008.

Badia, A., Serra, P., Modugno, S., 2011. Identifying dynamics of fire ignition probabilities in two representative Mediterranean Wildland Urban Interface areas. Applied Geography. 31, 930-940. https://doi.org/10.1016/j.apgeog.2011.01.016.

Berry, B.J.L., 1976. The counterurbanization process: Urban America since 1970. In Berry, B.J.L. (ed.) Urbanization and counterurbanization. Beverly Hills: Sage, 17-30

Bertrand, C., Bertrand, G., 2006. Geografía del medio ambiente. El sistema GTP: Geosistema, Territorio y Paisaje. Granada: Universidad de Granada

Boada, M., Saurí, D., 2002. El canvi global. Barcelona: Editorial Rubes.

Bond, W. J.; Keane, R., 2017. Fires, ecological effects of. Reference Module in Life Sciences, USDA Forest Service. https://doi.org/10.1016/B978-0-12-809633-8.02098-7.

Butsic, V., Kelly, M., Moritz, M.A., 2015. Land use and wildfire: A review of local interactions and teleconnections. Land, 4, 140-156. http://doi.org/10.3390/land4010140.

Butler, C.P., 1976. The urban/wildland fire interface. Fire Prevention Notes, California Department of Forestry, 10.

Caballero, D., Beltrán I., Velasco, A., 2007. Forest fires and wildland urban interface in Spain: Types and risk distribution. Wildfire.

Cohen, J.A., 1960. Coefficient of agreement for nominal scales. Educational and Psychological Measurement, 20, 37-46.

CORDIS, n.d. FIRE STAR. A decision support system for fuel management and fire hazard reduction in Mediterranean Wildland-Urban Interfaces. CORDIS, European Commission. https://cordis.europa.eu/project/rcn/61220/factsheet/en. Accessed 18 Dec 2019

Cortnet, H.J., Gardner, F.D., Taylor, J.G., 1990. Fire hazards at the urban-wildland interface: What the public expects. Environmental Management, 14(1), 57-62. http://dx.doi.org/10.1007/BF02394019

Council of Europe, 2016. European Landscape Convention (ELC). http://www.coe.int/t/dg4/cultureheritage/heritage/Landscape/default_en.asp Accessed 18 Dec 2019.

Costa, P., Castellnou, M., Larrañaga, A., Miralles, M., Kraus, D., 2011. La prevenció dels grans incendis forestals adaptada als incendis tipus. Fireparadox. Unitat Tècnica del GRAF. Generalitat de Catalunya

CREAF, 2010. Interpretació de les llegendes de les diferents edicions del mapa de cobertes del sòl de Catalunya. Cerdanyola del Vallès: Universitat Autònoma de Barcelona

CREAF, 2016. http://www.creaf.cat/ Accessed 18 Dec 2019.

Cussó, X., Garrabou, R., Tello, E., 2006. Social metabolism in an agrarian region of Catalonia (Spain) in 1860-1870: Flows, energy balance and land use. Ecological Economics, 58, 49-65. https://doi.org/10.1016/j.ecolecon.2005.05.026.

Davis, J.B., 1990. The wildland-urban interface: Paradise or battleground? Journal of Forestry, 88(1), 26-31.

Davis, M., 1995. The case of Malibu burn. Environmental History Review, 19(2), 1-36. https://doi.org/10.2307/3984830

Dunning, J.B., Danielson, B.J., Pulliam, H.R. 1992. Ecological processes that affect populations in complex landscapes. Oikos 65, 169-175. doi:10.2307/3544901

Echeverría, C., Coomes, D., Salas, J., Rey-Benayas, J.M., Lara, A. Newton, A., 2006. Rapid deforestation and fragmentation of Chilean temperate forests. Biological Conservation, 130, 481-494. https://doi.org/10.1016/j.biocon.2006.01.017

European Environment Agency (EEA), 2006. Urban sprawl in Europe. The ignored challenge. EEA Report No 10/2006. European Commission, Joint Research Centre. Luxembourg

Environmental Systems Research Institute (ESRI), 2016. http://www.esri.com/ Accessed 18 Dec 2019.

Food and Agriculture Organisation (FAO), 1996. Forest resources assessment 1990. Survey of tropical forest cover and study change process. FAO Forestry Paper 130. ISSN 0258-6150.

Farina, A., 1991. Recent changes of the mosaic patterns in a montagne landscape (north Italy) and consequences on vertebrate fauna. Options Méditerranéennes, 15, 121-134.

Flannigan, M., Cantin, A.S., de Groot, W.J., Wotton, M., Newbery, A., Gowman, L.M., 2013. Global wildland fire season severity in the 21st century. Forest Ecology and Management, 294, 54-61. http://dx.doi.org/10.1016/j.foreco.2012.10.022

Forman, R.T.T., 1995. Land mosaics: The ecology of landscapes and regions. Cambridge: Cambridge University Press.

Galiana, L., 2012. Las interfaces urbano-forestales: un nuevo territorio de riesgo en España. Boletín de la Asociación de Geógrafos Españoles, 58, 205-226.

Galiana-Martin, L., Herrero, G., Solana, F., 2011. A Wildland Urban Interface typology for forest fire risk management in Mediterranean areas. Landscape Research, 36(2), 151-171. https://doi.org/10.1080/01426397.2010.549218

Greene, D.F., Michaletz, S.T., 2015. The role of fire in forest ecosystems. Routledge Handbook of Forest Ecology. ISBN: 9780415735452.

Henry, G., 2004. Los costes económicos y sociales de la ciudad de baja densidad. Seminar: La ciudad de baja densidad: lógicas, gestión y congestión, November 24-26. Barcelona: Consorcio Universidad Internacional Menéndez Pelayo de Barcelona, Center Ernest Lluch.

Herrero, G., 2011. Las interfaces urbano forestales como territorios de riesgo frente a incendios: análisis y caracterización regional en España. Dissertation, Universidad Autónoma de Madrid.

Indovina, F., 1990. La città diffusa. Venetia: Daest.

Kitada, K., Fukuyama, K., 1912. Land-use and land-cover mapping using a gradable classification method. Remote Sensing, 4, 1544-1558. http://doi.org/10.3390/rs4061544.
Landscape Observatory of Catalonia, s.n. Documentation Centre. Glossary http://www.catpaisatge.net/eng/glossari.php. Accessed 18 Dec 2019.

Mather, A.S., 1992. The forest transition area. 24(4), 367-379.

Miller, F., Osbahr, H., Boyd, E., Thomalla, F., Bharwani, S., Ziervogel, G., Walker, B., Birkmann, J., van der Leeuw, S., Rockström, J., Hinkel, J., Downing, T., Folke, C., Nelson, D., 2010. Resilience and vulnerability: Complementary or conflicting concepts? Ecology and Society. 15(3), 11.

Minnich, R.A., 1987. Fire Behavior in Southern California Chaparral before Fire Control: The Mount Wilson Burns at the Turn of the Century. Annals of the Association of American Geographers, 77(4), 599-618. doi:10.1111/j.1467-8306.1987.tb00183.x.

Modugno. S., Balzter, H., Cole, B., Borrelli, P., 2016. Mapping regional patterns of large forest fires in Wildland-Urban-Interface areas in Europe. Journal of Environmental Management, 172, 112-126. https://doi.org/10.1016/j.jenvman.2016.02.013.

Muñoz, F., 2004. Urbanalització. La producció residencial de baixa densitat a la província de Barcelona, 1985-2001. Biblio 3W, Revista bibliográfica de geografía y ciencias sociales (Serie documental de Geo Crítica). Barcelona: Universidad de Barcelona IX (528).

Myszewski, M., Kundell, J.E., 2005. Land use planning and zoning at the wildland-urban interface. In: S W Vince, M L Duryea, E A Macie et al (eds.) Forests at the wildland-urban interface: Conservation and management. Boca Raton: CRC Press, 77-94.

Nguyen, L.H., Deepak R.Joshi, D.R., Clay, D.E., Henebry, G.M., 2018. Characterizing land cover/land use from multiple years of Landsat and MODIS time series: A novel approach using land surface phenology modeling and random forest classifier. Remote Sensing of Environment. In Press. https://doi.org/10.1016/j.rse.2018.12.016.

Nogué, J., 2007. La construcción social del paisaje. Madrid: Biblioteca Nueva.

Observatori del paisatge, n.d. http://www.catpaisatge.net/eng/index.php Accessed 18 Dec 2019.

Otero, O., Nielsen, J., 2017. Coexisting with wildfire? Achievements and challenges for a radical socialecological transformation in Catalonia (Spain). Geoforum, 45, 234-235. https://doi.org/10.1016/j.geoforum.2017.07.020.

Otero, I., Boada, M., Tábara, J.D., 2013. Social-ecological heritage and the conservation of Mediterranean landscapes under global change. A case study in Olzinelles (Catalonia). Land Use Policy, 30(1), 25-37. https://doi.org/10.1016/j.landusepol.2012.02.005.

Plana, E., 2011. Integració del risc d'incendis en la planificació forestal estratègica i l'ordenació del territori. Treballs de la Societat Catalana de Geografia, 71-72, 69-91.

Radeloff, V.C., Hammer, R.B., Stewart, S.I., Fried, J.S., Holcomb, S.S., Mckeerry, J.F., 2005. The wildland-urban interface in the United States. Ecological Applications, 15(3), 799-805. https://doi.org/10.1890/04-1413.

Rudel, T.K., Coomes, O.T., Moran, E., Achard, F., Angelsen, A., Xu, J., Lambin, E., 2005. Forest transitions: Towards a global understanding of land use change. Global Environmental Change, 15, 23-31. https://doi.org/10.1016/j.gloenvcha.2004.11.001.

Rudel, T.K., Schneider, L., Uriarte, M., 2010. Forest transition: An introduction. Land Use Policy. 27(2), 95-97. https://doi.org/10.1016/j.landusepol.2009.09.021.

Sala, O.E., Chapin, F.S., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M., Poff, N.L., Sykes, M.T., Walker, B.H., Walker, M., Wall, D.H., 2000. Global biodiversity scenarios for the year 2100. Science, 287, 1770-1774. doi: 10.1126/science.287.5459.1770.

Stewart, S.I., Radeloff, V.C., Hammer, R.B., Hawbaker, T.J., 2007. Defining the wildland–urban interface. Journal of Forestry, 105, 201-207

Theobald, D.M., Romme, W., 2007. Expansion of the US wildland-urban interface. Landscape and Urban Planning, 83(4), 340-354. https://doi.org/10.1016/j.landurbplan.2007.06.002.

Turner, M.G., 2005. Landscape ecology: What is the state of the science? Annual Review of Ecology, Evolution, and Systematics, 36, 319-44. https://doi.org/10.1146/annurev.ecolsys.36.102003.152614.

Turner II, B.L., 2010. Vulnerability and resilience: Coalescing or paralleling approaches for sustainability science? Global Environmental Change, 20, 570-576. https://doi.org/10.1016/j.gloenvcha.2010.07.003.

Turner II B.L., Lambin, E.F., Reenberg, A., 2007. The emergence of land change science for global environmental change and sustainability. Proceedings of the National Academy of Science, 104, 20666-20671. doi:10.1073/pnas.0704119104.

UNESCO, 2008. Operational guidelines for the Implementation of the World Heritage Convention (UNESCO Paris) aim to facilitate the implementation of the 1972 Convention Concerning the Protection of the World Cultural and Natural Heritage (referred to as the World Heritage Convention). (Decision 6 EXT.COM 5.1). http://whc.unesco.org/en/guidelines/ Accessed 18 Dec 2019

United States Department of Agriculture (USDA), 2001. Urban Wildland Interface Communities within the vicinity of Federal lands that are at high risk from wildfire. 66 Federal Register, 753, Doc. No.: 01-52.

Vélez, R., 2000. Perspectiva histórica de los incendios forestales en España. In: Vélez R. (ed.) La Defensa Contra Incendios Forestales: Fundamentos y Experiencias. Madrid: McGraw Hill España.

Viedma, O., Moreno, J.M., Rieiro, I., 2006. Interactions between land use/land cover change, forest fires and landscape structure in Sierra de Gredos (Central Spain). Environmental Conservation, 33(03), 212-222. http://doi.org/10.1017/S0376892906003122.

Viegas, X. (ed.) 2009. Recent Forest Fire Related Accidents in Europe. EUR 24121 EN – 2009. Joint Research Centre, European Commission.

Vince, S.W., Duryea, M.L., Macie, E.A. Y Hermansen, A. (eds.). Forests at the wildland-urban interface: conservation and management. Boca Raton: CRC Press, 293 p.

WARM CORDIS, n.d. Wildland-urban area fire risk management. European Commission. https://cordis.europa.eu/project/rcn/59893/factsheet/en. Accessed 18 Dec 2019.

WUIWATCH. n.d. Wildland - Urban Interface Forest Fire Risk Observatory and Interest Group in Europe. European Civil Protection and Humanitarian Aid Operations Service tools. European Commission. https://www.wuiwatch.org/ Accessed 18 Dec 2019