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Increased vulnerability to wildfires and post fire hydro-geomorphic processes in Portuguese mountain regions: what has changed?

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Abstract: The main objectives of this study were to understand the frequency of forest fires, post-fire off-site hydrological response and erosional processes from a social and ecological perspective in two basins located in the central cordillera, Portugal. It also discusses the driving forces that contribute towards increasing the social–ecological vulnerability of systems in the face of hazards and emphasizes the importance of learning from disasters. Based on the historical incidence of wildfires, it is possible to identify several areas affected by two, three or four fires, since 1975. Following the two major fires, in 1987 and 2005, flash floods, intense soil erosion and sedimentation processes were generated, causing severe damage. Significant socioeconomic, political and ecological changes have been affecting mountain regions in the last decades. Approximately 80% of the population and more than 90% of the livestock have disappeared, common lands have been afforested with *Pinus pinaster*, and several agricultural plots have been abandoned. These factors have all contributed towards creating non- or sub-managed landscapes that have led to a dramatic increase in the magnitude and frequency of wildfires and to post-fire hydrological and erosional processes when heavy rainfall occurs. Moreover, the low population density, high level of population ageing and very fire-prone vegetation that now covers large areas of both basins, contribute to a situation of extreme socio-ecological vulnerability, meaning that disasters will continue to occur unless resilience can be restored to improve the capacity to cope with this high susceptibility to hazards.

Keywords: Wildfires; Flash floods; Erosive processes; social and ecological vulnerability; Mountains of Central Portugal

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1 Introduction

Mountain areas are vital and complex systems that provide biodiversity, water resources, valuable habitats, energy, fresh air and recreational sites, and are also part of our cultural heritage. According to Hewitt (1997), since the last century mountains have become increasingly hazard-prone areas and a high number of disasters occur there, in comparison to other environments. In the mountainous regions of the Mediterranean basin, where forest fires have been increasing (JRC 2005), flash-floods and intensive erosion processes seem to have become more regular, since the climate is characterized by heavy rainfall due to deep, intense cyclones (Jansa et al. 2014) and a complex topography. In fact, mountain regions are much more geophysically and hydrologically active in comparison to lowland areas. A better understanding of hazards and consequent disasters must therefore be based on knowledge of the bio-geophysical conditions and human dimensions (Blaikie et al. 1994; Klinenberg 2002).

In Portuguese mountain areas, as in other Mediterranean countries, socioeconomic development has been affected by physical constraints, an inadequate road network, lack of industry, limitations on trade, reduced competitiveness and lack of tourism facilities. As a result, there has been an ongoing process of population migration in recent decades, which has increased demographic and structural problems and farmland abandonment. These changes are frequently followed by a significant loss of natural and cultural landscapes, a decline in biodiversity, an increase in natural hazards, the deterioration of forest land, forest fires, soil deterioration, water pollution, etc. (Dax and Wiesinger 1998; García-Ruiz and Lana-Renault 2011; Lourenço et al. 2012; Nunes and Lourenço 2013; Lourenço and Nunes 2014).

Various authors have reported alterations in the fire regime, both in terms of higher fire recurrence and incidences of major events (Vazquez and Moreno 2001; Lloret et al. 2003), which may have significant consequences for Mediterranean ecosystems. Wildfires can greatly increase the landscape's susceptibility to major flooding and erosion (Moody and Martin 2001; Mayor et al. 2007; Shakesby and Doerr 2006; Stoof et al. 2012; Soulis et al. 2012; Moody et al. 2013; Nyman et al. 2013). DeBano (2000) and Loaiciga (2001) consider that forest fires increase the magnitude of runoff and erosion and change the hydrological response of watersheds resulting from subsequent rainfall, creating a risk for downstream communities that lasts 1-3 years after a fire. Other authors (Doehring 1968; Helvey 1980; Shakesby 2011) extend the "window of disturbance" to a much longer period of 3–10 years.

Consequently, the nature of mountain social–ecological systems and the vulnerability of people and property to natural hazards have changed. Maikhuri et al. (2003) consider that vulnerability may be defined as the extent to which environmental and economic changes influence the capacity of human and ecological systems to respond to natural and socioeconomic shocks. The most vulnerable systems would therefore be the ones that are most exposed to disturbance, have a limited capacity to adapt and are least resilient (Liechenko and O'Brien 2002). For the United Nations (UNISDR 2009), vulnerability reflects the physical, social, economic and environmental conditions which increase the susceptibility of a community to the impact of hazards. In this sense, vulnerability is the combined result of three main components: i) *Exposur*e, representing the presence of elements (people, property, ecosystems) that may be subject to losses (UNISDR, 2009); ii) *Sensitivity*, reflecting the predisposition of the exposed elements to suffer certain types and magnitudes of losses (Birkmann et al. 2013; Cutter 2011); iii) *Coping Capacity*, related to the measures applied to anticipate potential effects or respond to fire (Birkmann et al. 2013; Tedim et al. 2013). Gardner and Dekens (2007) suggest that as vulnerability increases, resilience decreases. The same authors consider that resilience is the corollary of vulnerability or, in other words, that vulnerability describes a condition of exposure, while resilience refers to processes that come into play during and after an event and enable a social–ecological system to carry on, perhaps in an altered state.

The main purpose of this work was to understand the multiple conditions or factors that contribute towards making mountain areas more vulnerable to the incidence and recurrence of forest fires, post wildfire runoff and erosion response in two basins located in the most important mountainous area of Portugal, the central cordillera. Specific objectives were to: i) analyse the incidence and recurrence of wildfires in recent decades; (ii) understand the most common causes of flash floods and debris flows triggered after wildfires; (iii) identify the main factors that contribute towards making the study area more exposed and sensitive to these cascade disasters; and (iv) discuss the importance of learning from disasters in order to enhance the resilience and sustainability of social–ecological systems. In fact, understanding the conditions that contribute to increased exposure and sensitivity to these natural hazards, and highlighting the importance of learning from disasters are absolutely vital to defining civil and environmental protection measures, planning more suitable prevention measures and allocating civil protection resources more effectively.

2 Material and methods

2.1 Study area

The study area covers two basins located between 40°13' and 40°17' N and 7°47' and 7°54' W Greenwich in the mountains of central Portugal: the Piódão and Pomares basins (Figure 1). Both rivers are tributaries of the River Alva. The Piódão and Pomares basins are 34.3 and 44.7 km^2, respectively. The elevational gradients exceed 1000m asl, and more than 90% of the basin areas have slopes of over 20%. The study area is located in the Hespheric Massif, the main physiographic unit of Portugal. The catchments lie on Precambrian schist and greywackes and the soils are predominantly Umbric leptosol, i.e. very shallow and stony soils.

The climate of the study area is classified as a Mediterranean climate Csb type according to the Köppen classification. In general, it is characterised by cool, wet winters and hot, dry summers. The mean annual rainfall is around 1600/1700 mm but is subject to great seasonality. Rainfall is normally concentrated in the period from October to May, whereas July and August are dry months.

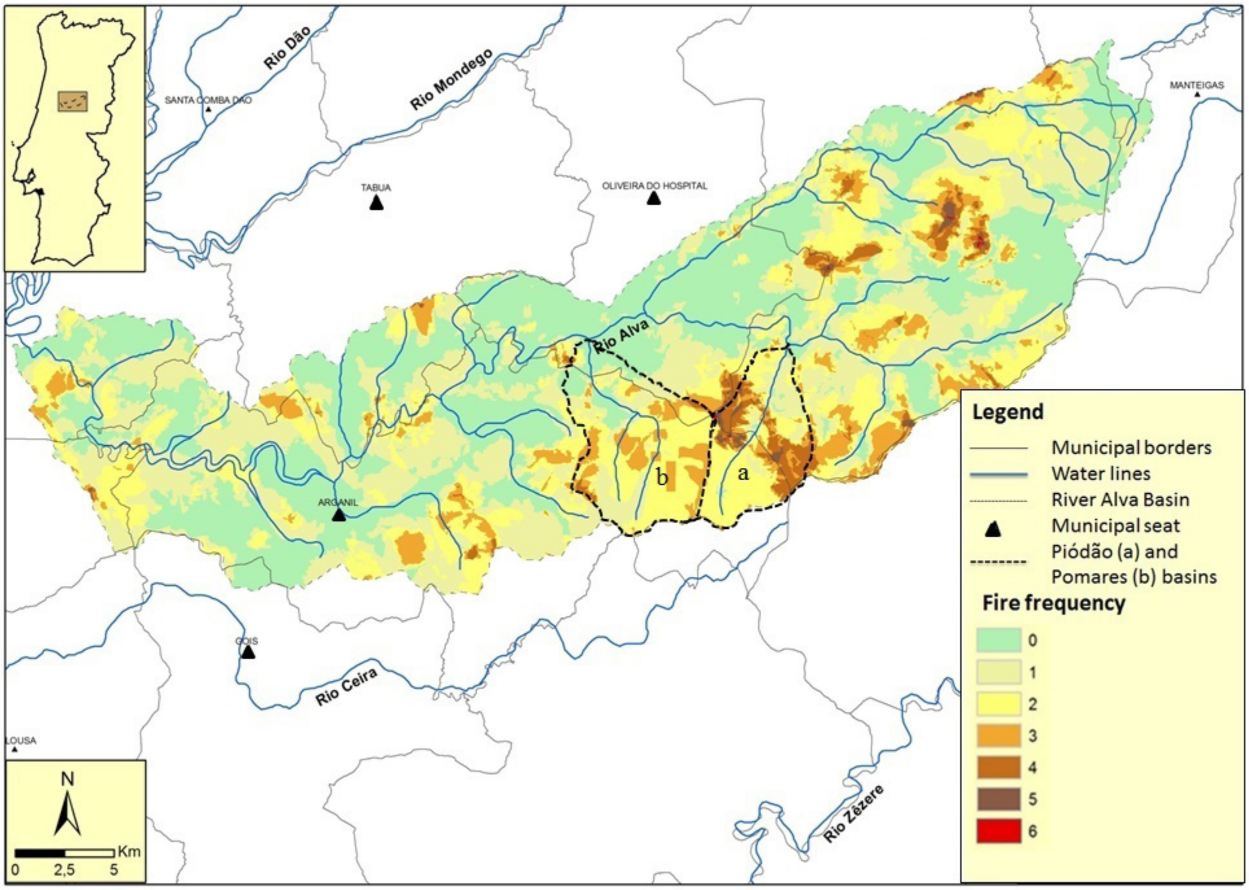

Figure 1. Location of the Piódão and Pomares basins in the River Alva basin, and fire frequency between 1975 and 2013

2.2 Methodology

The historical wildfire database for the study area was compiled from the Portuguese National Institute for Nature Conservation and Forestry (ICNF) data. The ICNF offers geographic information system (GIS) datasets that comprise polygon features representing wildfire perimeters with a burnt area of over 10ha, since 1991. The datasets from 1975 to 1990 were obtained from Oliveira (2008) and Oliveira et al. (2011).

Using GIS software (ESRI), a map of incidence and recurrence was generated, including only wildfires greater than 10ha. The modelling process implemented in ArcGIS (ArcGIS, 10.1, ESRI) showing information relating to occurrences of fires had to be organized into individual ‘‘layers’’ according to the year of incidence. This information was then converted to raster format and codified according to the existence of burnt areas - e.g. ‘‘0’’ for unburnt areas and ‘‘1’’ for areas affected by fire once, “2” for areas affected by fire twice. The information was converted and combined into a final raster output which summarized all the previous information. It was then possible to create a map showing the spatial frequency of burnt areas at various times and the pattern of recurrence throughout the period analysed.

As both watersheds are ungauged, the post-fire hydrological and erosional responses were analysed by exhaustive fieldwork in order to understand the spatio-temporal heterogeneity of these processes. The fieldwork was carried out immediately after the events occurred and aimed to identify specific features, such as high-water marks left by the flow, sediment transport processes (erosion and deposition on slopes and in river beds), edge effects on the vegetation and the transport and deposit of vegetation fragments. Local knowledge of events and the catchment characteristics proved to be very important.

A rain gauge installed in the Piodão basin in 2005 and 2006 was crucial to understanding the meteorological characteristics during the two storms that affected the area in June and July 2006.

Several authors (Hershfield 1961; Miller et al. 1973; Moody and Martin 2001) consider that in mountainous areas around 80% of the hourly precipitation has a short duration of within 30 minutes. Daily and 30-minute rainfall intensity measures (I_{30}) were therefore chosen to characterise the most recent events. For the event that occurred in June 1988, the information on daily rainfall was collected from a rain gauge located in Arganil (Lat: 40.21' N; Long: 8.052' W gr; Alt: 199 m).

In order to understand the growing exposure and sensitivity to natural hazards, a set of components, representing historical changes in social, economic, environmental and political trajectories were analysed. This data was compiled using information from national bodies (statistical variables, such as population and livestock data were obtained from national statistics, whilst information on land use and cover change was based on cartography produced by the Agrarian Survey and Management Service for 1972, and the Land Use and Land Cover Map of Continental Portugal for 2007 from the Directorate-General for Territorial Development (both at 1:25000 scale), journals and other reliable sources. The quantitative analyses of the terraced land in both basins were initially based on aerial photos from 1958, followed by intensive field work in order to check the current state of conservation.

3 Results and discussion

3.1 Burnt areas in the period 1975–2013 and fire frequency

The total annual burnt area for the entire Alva river basin during the period 1975-2013 is shown in Figure 2. In total, about 77 000 ha were devastated by wildfires covering ≥ 10 ha, with a particular focus on the years 1987 and 2005, in which more than 10 000 ha were recorded. Figure 1 shows the fire recurrence map for the whole Alva Basin. As can be seen, in the Piódão and Pomares basins almost the whole area was burnt and it is possible to identify several areas affected two, three or four times by fires (see Figure 1 in the section study area). Two forest fires affected the greater part of both catchment areas: the first took place between 13th and 20th September 1987 burning 10 900 hectares; the second, occurring eighteen years later between 19th and 24th July 2005, which affected an area of 17 450 hectares (Lourenço 2006a, 2006b, 2007).

In analysing the trend in burnt areas for the period 1980-2014 at municipal level, Nunes et al. (2016) detected significant negative trends prevailing in 5% of the municipalities, mainly located in the central region of Portugal, including the municipality where both basins are located. A negative trend was also found for the Alva river basin since 1975, although it has no statistical significance (p-value >0.05).

Taking into account the two more catastrophic events, which affected the greater part of both basins, the fire cycle (typical fire return intervals) agrees with other findings for Mediterranean mountain regions over a period of around 13 years.

3.2 Post-fire flash floods, debris flows and related disasters

Following the two large fires of 1987 and 2005, flash floods, intense soil erosion and sedimentation processes were generated and several areas of both basins were affected. The first episode occurred approximately 8 months after the great fire of September 1987, on June 23rd 1988. During this month significant daily quantitative

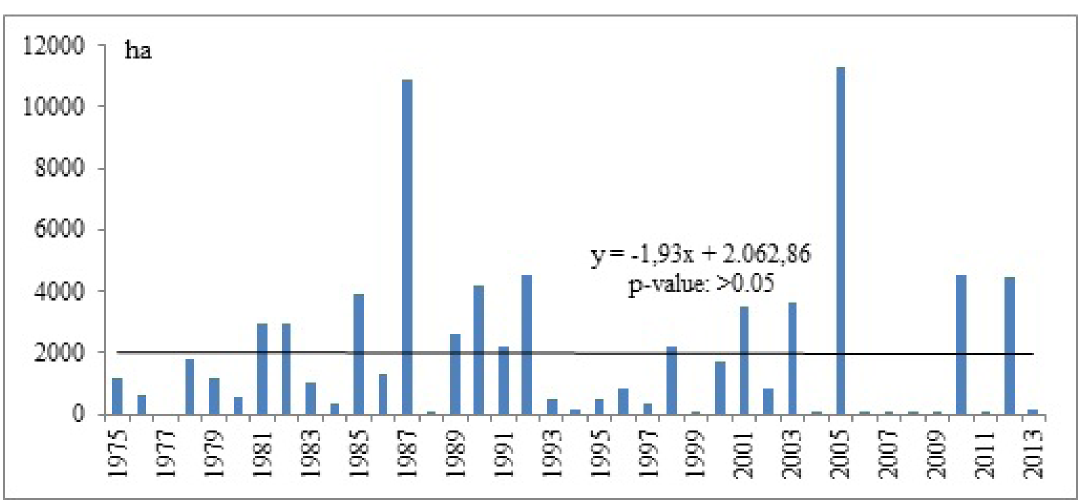

Figure 2. Evolution of the burnt area between 1975 and 2013 (sum of wildfires covering ≥ 10 ha)

rainfall was recorded in the nearest rain gauge station, located in Arganil at about 200 meters asl. The highest rainfall figures occurred on 21st and 23 rd, exceeding 70mm per day. The heavy precipitation recorded on 23rd, certainly amplified by the orographic effect and associated with the destruction of vegetation cover by the fire: enhanced runoff generated in the upstream areas; led to the rupture of dykes; destroying crops; damaged a house; and made the square in the village of Sargaçosa impassable.

Nearly two decades later, two storms with similar characteristics to the one that occurred in 1988 also generated flash floods, intense soil erosion and sedimentation processes in several areas of the Pomares and Piodão basins. In fact, high levels of precipitation during two main events on 16th June and 14th July 2006 were recorded around one year after the 2005 forest fire. A rain gauge placed in the Piódão basin recorded 58mm over 5 days in June 2006. About half of the total precipitation was concentrated on the 16th June, and 22 mm were registered between 5 pm and 6 pm. As a consequence of such concentrated precipitation, an extreme water level was recorded at Pomares Bridge (in the Pomares river basin), flooding the river banks (Figure 3). The inability to drain off the volume of water that had accumulated during the intense precipitation, as well as the streamflow transporting materials, causing the obstruction and blocking the Vide footbridge, increased the level of the water and the flood area.

Figure 3 (a and b) shows the streamflow level and tonnes of material, mainly branches of trees and shrubs, carried downstream, resulting in bridge and footbridge obstruction. Numerous flood marks were evident upstream, as can be seen in the map in Figure 4. In the Piódão basin the hydrological effects were also visible, particularly affecting the river beaches (Figure 4), where flash floods were registered. Figure 3c shows a plan of the debris flow deposition caused by the failure of the drainage ditches to cope with the enhanced runoff generated in the upstream areas and the soil erosion, which led to flooding and the accumulation of large boulders.

The rainfall recorded in July 2006 amounted to 95 mm. Around 70 mm of rain fell in two days, on 13th and 14th July. The precipitation recorded on 14th July was concentrated in one single event that occurred between 4 pm and 5 pm. The total precipitation in the first half hour was 14 mm, followed by 25 mm in the following 30 minutes.

In comparison to the June 16th event, this event was more localized, mainly affecting the Piódão stream headwaters. The intense precipitation considerably increased the streamflow quantity, resulting in a stronger and faster response which led to downstream floods and severe damage due to sediment transport. Figure 5a shows the volume of water accumulated in both events at the Piódão river beach and demonstrates that the maximum level was higher during this event than the previous one. The flood marks on the house used to estimate the maximum water flow show that the ground floor was not flooded in the 16th June event, whereas during 14th July flash flood the building was flooded to a depth of 1 meter. The image also shows the tonnes of material, mainly sediment, carried downstream and intercepted by the dyke. A road and a car park near the centre of Piódão were partially destroyed by the water, causing a landslide (Figure 5b). The erosive power of the overland flow also resulted in deeply incised channels, such as rills and gullies, and accelerated the removal of material from the hill slopes. In addition to substantial damage to human infrastructures, one death was recorded. The force of the water demolished a bridge as a tourist was crossing, causing his death.

Figure 3. Post-wildfire effects in response to the rainfall episode of 16th June 2006: a) maximum water level at Pomares Bridge; b) organic and sediment debris blocking the Vide footbridge, Alvoco river; c) regular flow at this season of the year, and sediment deposits after the wildfire in Soita da Ruiva

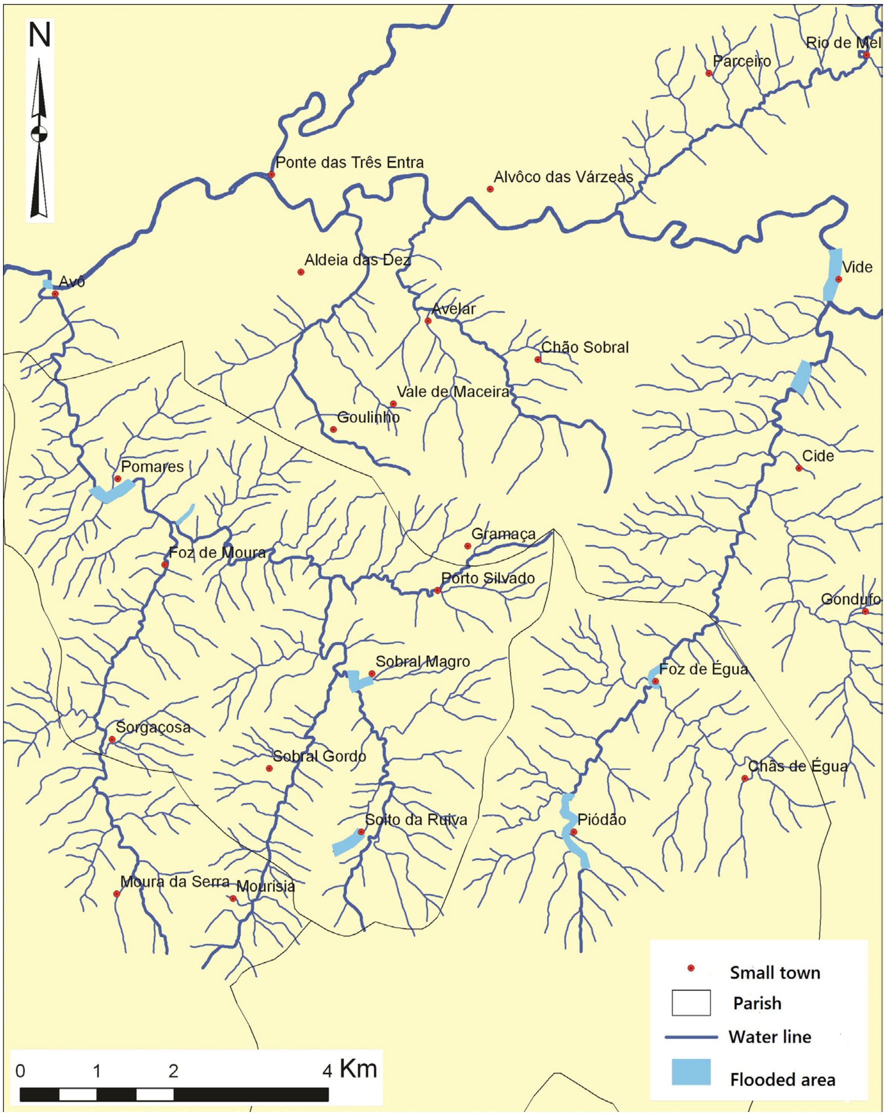

Figure 4. Flooded areas after the 16th June episode at the Piódão and Pomares basins

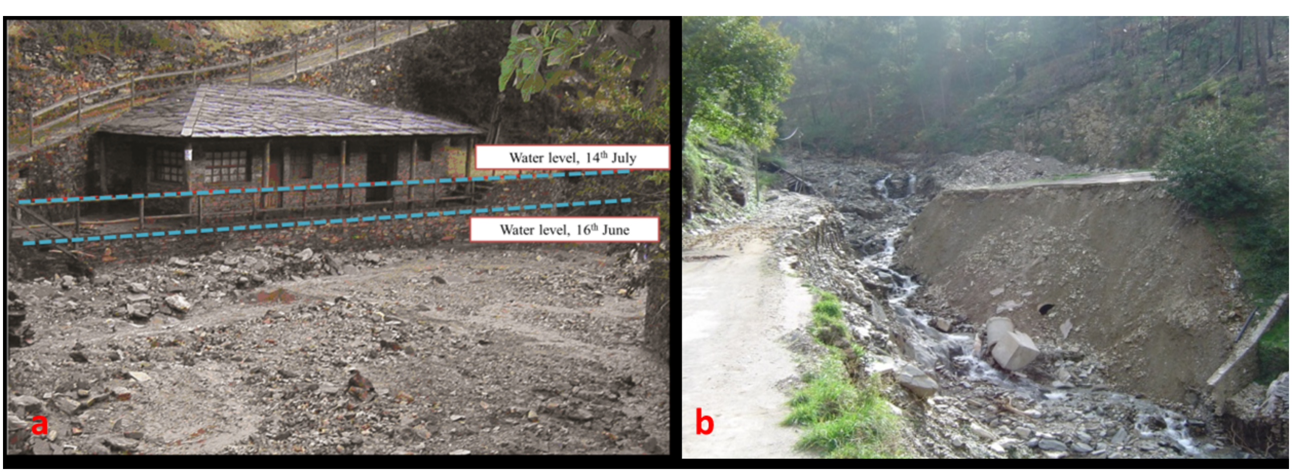

Figure 5. Post-fire processes after the precipitation event of 14th July 2006: a) comparative analysis of the water level on June 16th and July 14th 2006 at the Piódão river beach; b) A road destroyed by the force of the water and sediment transported along the main channel during the 14th July event

3.3 Increased vulnerability in the Piódão and Pomares basins: what has changed?

3.3.1 Social and economic changes

Mountain areas in Portugal have been affected by significant demographic and socioeconomic changes for at least the last five to six decades. Figure 6 shows the total population changes during the last century and the first decade of the 21st century in the study area. The parish of Piódão, for example, had a population of 1,088 inhabitants in 1960, which had fallen to 127 by 2011, representing an 84% loss. In the Pomares basin, migration started a few decades earlier at the beginning of 20th century and since then it has lost about 80% of its population. The population density is 4.9 people per km^2 in the parish of Piódão and 16.3 people per km^2 in Pomares. The average age of the remaining population is very high; according to the last census in 2011, the aging indexes are 800% and 407% for Piódão and Pomares, respectively.

The farmed area was larger at the peak of the region's demographic development during the first half of the 20th century. Most of the agricultural area was used for extensive herding, whilst more intensive forms of cultivation only existed at the foot of the mountain, in the valleys. The decrease in population led to the abandonment of agricultural land and a reduction in livestock. There was a significant decrease in the total number of sheep and goats during the last century, totalling 95% and 90% respectively in the Pomares and Piódão parishes (Figure 6).

On the other hand, the Portuguese government has promoted several afforestation campaigns, mostly involving "common lands" and the planting of maritime pine trees, due to their fast growth and the low cost of seeding. In both parishes, around 40% of the land was organized under a common property system, meaning that it was managed by local people with common rights.

The implementation of the 1938 afforestation plan in the common lands of the northern and central regions had a severe impact on the dynamics of the landscape and local social and economic conditions, since the commons were an important component of the poor rural economy in mountain villages and were used mainly for grazing livestock and cutting brushwood.

As a result, according to Agrarian Survey and Management Service (1972) cartography, in the middle of the last century more than 70% of both basins were occupied by *Pinus pinaster*, a very inflammable specie. In fact, in the 1950s and 60s, *Pinus pinaster* was planted in the common lands and also in some agricultural fields and pastures abandoned due to the rural exodus.

More recently, the natural disadvantages of such mountainous areas were recognized under the EU Common Agricultural Policy (CAP) and they received structural support as 'Less-Favoured Areas' (LFAs, Regulation 950/97). Thus, the implementation of CAP measures in Mediterranean countries has been reinforced by extensification in the LFAs, i.e. abandonment or marginalization and the collapse of traditional farming systems, which has been ongoing for decades.

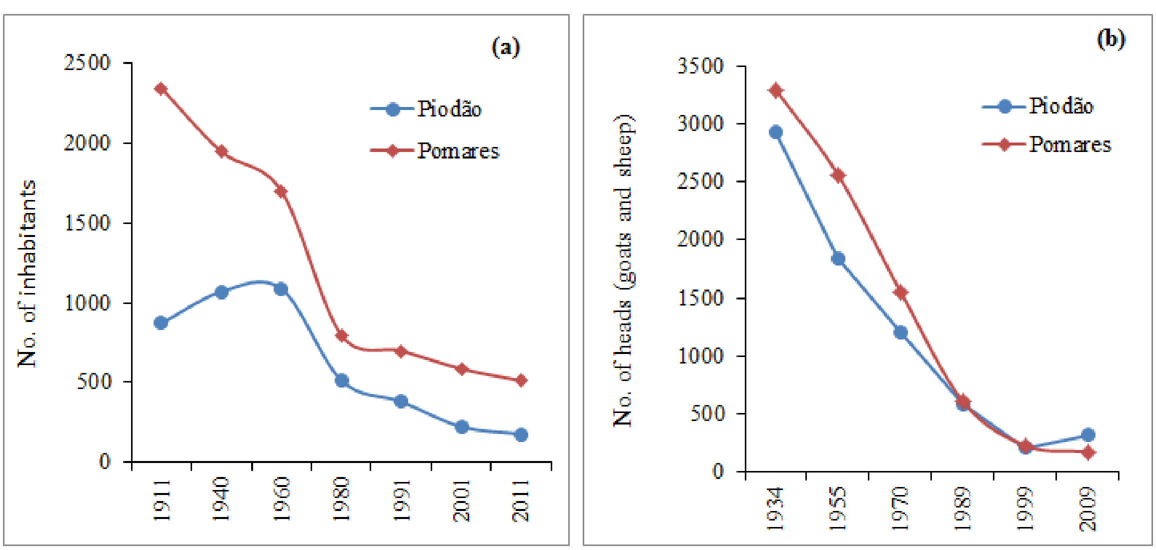

Figure 6. Evolution of the total population (a) and livestock (goats and sheep) (b) Source: a. "Recenseamento Geral da População": 1911, 1940, 1960, 1980, 1991, 2001 and 2011, Instituto Nacional de Estatística; b. "Arrolamento Geral de Gados e Animais de Capoeira": 1934, 1955 and 1970; "Recenseamento Agrícola do Continente": 1989, 1999 and 2009, Instituto Nacional de Estatística

Mountainous areas in Portugal, as well as in Mediterranean Europe, have now become marginal areas affected by radical changes to the landscape.

Rural and forest areas are to a large extent deserted due to the abandonment of farming activities and the decrease in biomass use (and also the transition to other energy sources such as fossil fuels, making the domestic use of biomass and its use in some industrial activities redundant), thus creating non- or sub-managed landscapes that have led to a dramatic increase in the magnitude and frequency of forest fires (Moreira *et al.*, 2011; Nunes, 2012). In fact, the impressive afforestation measures implemented in common and private lands during the 20th century were not followed by proper forest management, silviculture and fuel-hazard reduction, especially after the 1970s (Mateus and Fernandes 2014).

Although fire is often vital to maintaining the status of pine in ecosystems, it is also a major hazard in plantations and the most significant threat to Pinus forests in the Mediterranean Basin (Barbéro et al. 1998; Fernandes and Rigolot 2007). Shakesby et al. (1996) also consider that afforestation focussing on highly inflammable species, mainly maritime pines, greatly favours the proliferation of forest fires. Once fires break out under highly dangerous conditions (meteorological and geographical conditions such as rugged topography and difficult access), they spread more easily and cannot be stopped.

Nowadays, the most common land cover is open trees, shrubs, grass and other light vegetation, which is very prone to fire (around 90% and 62% of the total area of the Piodão and Pomares parishes, respectively) (Figure 7). Several studies confirm that this land cover is one of the types most seriously affected by wildfires (Nunes et al. 2005; Sebastián-López et al. 2008; Catry et al. 2009; Moreira et al. 2009; Bajocco and Ricotta 2008; Nunes 2012; Carmo et al. 2011; Oliveira et al. 2012; Ganteaume and Jappiot, 2013; Oliveira 2014; Nunes et al. 2016). Conversely, Nunes et al. (2016) found that in Portugal at municipal level, traditional activities based on agriculture, grazing and forestry seem to reduce the burnt area, suggesting that the survival of Mediterranean silvopasture activities reduces the frequency and impact of forest fires.

3.3.2 Ecological changes

Other ecological changes have also taken place in addition to changes in the landscape associated with the increase in land afforested with *Pinus pinaster*, the abandonment of traditional agriculture and the reduction in herds, which have altered the vegetation structure and favour horizontal and vertical fuel continuity and a consequent increase in flammable biomass.

In mountains areas, terraces are the most common soil conservation practice used throughout the world (Bokhtiar et al. 2001; Kasai et al. 2001) and are entirely man-made. The key function of these structures, in the past as well as in the present, has been to increase the usefulness of steep slopes. Terracing reduces the steepness of slopes and divides them into short, gently inclining sections (Morgan

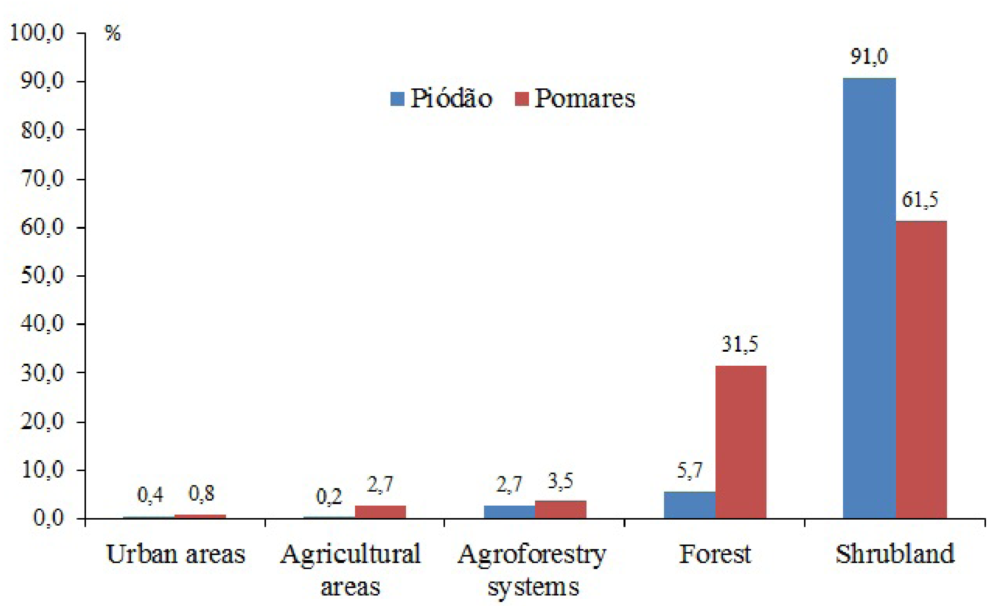

Figure 7. Land use and land cover in the Piódão and Pomares parishes in 2007

1986), thus increasing the planting area and the potential for agriculture. The other main purposes of terracing are to intercept surface runoff and reduce the loss of soil, therefore increasing the soil moisture content through improved infiltration and by reducing peak river discharge rates.

In the study areas, the terrace occupancy rate is 15.8 and 9.1% in the Pomares and Piodão basins, respectively (Table 1). Around 60% of these terraces had remained in good condition until recently. The remaining 40% are in poor condition or completely destroyed. In fact, terrace conservation on steep slopes requires a great deal of human labour and once the terraces were abandoned, due to changing demographic and economic conditions, the drainage system became ineffective, resulting in soil saturation and massive soil movements.

Table 1. Occupancy of terraces in the Pomares and Piodão basins

	Area (km^2)	Terraces (in km^2)	Occupancy Rate (in %)	Walls (in km)
Pomares basin	45	7.1	15.8	77.9
Piodão basin	34	3.1	9.1	97.8

The destruction of vegetal protection, particularly after forest fires, has led to destructive erosion, leading to the slumping and collapsing of terraces. In fact, the most important erosion process observed in the terraced fields was the collapse of terrace walls, as a consequence of massive soil movement (small landslides) (Figure 8). Failure to maintain network ditches tends to produce a reorganization of the drainage system, due to the creation of new channels which cut across terraces and re-establish the natural drainage network. For this reason, stream channels frequently become another important source of sediment in abandoned areas (Llorens et al. 1992).

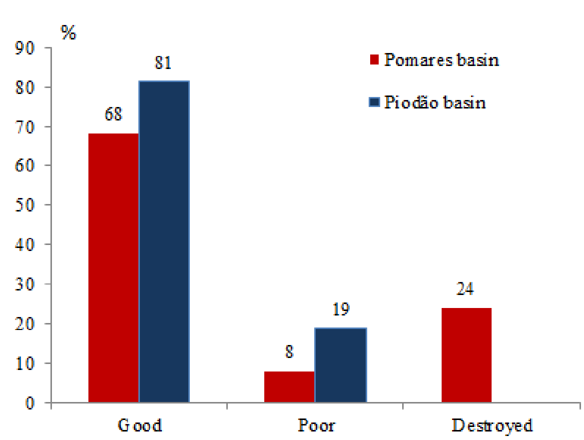

Figure 8. State of conservation of the terraced fields in 2010

3.3.3 Political and institutional changes

The historical incidence of forest fires in Portugal and the consequent need for strong prevention measures are addressed repeatedly in technical and scientific studies on forestry. By 1888 Sousa Pimentel already considered that forest fire prevention should be part of forestry management programmes. Although scientific knowledge highlights the concrete measures required to minimize the forest fire risk (Natividade 1950) this is not reflected in forestry policy. More recently, various national level strategic documents have been produced: the “Forest Policy Framework Law” in 1996; the “Portuguese Forest Sustainable Development Plan” in 1999; the “Action Plan for the Forest Sector” and the “Forest Sector Structural Reform” in 2003; the “Operational Plan for Forest Fire Prevention and Suppression” in 2005; the “National Forest Fire Defence Plan” (PNDCIF) (2006-2018)” and “National Forest Strategy” in 2006. This series of documents reflects the absence of any coherent long-term national policy for sustainable forestry, and they are based on fire management policies that are markedly reactive and inconsistent.

Following the catastrophic fire years of 2003 and 2005, the PNDCIF (ICNF 2006) established the fire management strategy and defined its goals and objectives, priorities and activities. The PNDFCI consists of five strategic axes of intervention namely: a) increasing fire resilience; b) reduction of fire incidence; c) increasing fire-suppression effectiveness; d) restoration of ecosystems; and e) adoption of a functional and effective organisational structure. Different agencies coordinate each of the three pillars of action: the Institute of Nature and Forest Conservation (ICNF), which is responsible for prevention; the National Republican Guard (GNR), which is responsible for for vigilance, fire detection and law enforcement; and the National Civil Protection Authority (ANPC), which is responsible for fire suppression. Although the PNDCIF refers to post-fire mitigation measures, they have not yet been implemented.

In fact, forest fires have revealed the limitations of a management policy which, as in other parts of the world, overemphasises extinction to the detriment of prevention (Mourão and Martinho 2016), and individual education to the detriment of more comprehensive rural development planning. In Portugal, Mateus and Fernandes (2014) estimate that fire pre-suppression and suppression absorbed 94% of the fire management budget in 2010.

3.4 Lessons Learned

The fragile balance of the mountain ecosystem was disrupted in the last century by several factors. The human exodus from mountainous areas, mainly due to poor agricultural conditions (a Mediterranean climate, rugged landscape, poor, shallow soils and afforestation of common lands), uncompetitive farm structures (small, scattered plots), lack of alternative employment, remoteness, and elderly farm owners, has meant that family agriculture and husbandry is no longer self-sustainable. Afforestation based on maritime pine, a fuel type that intensifies the likelihood of outbreaks of fire (Fernandes and Rigolot 2007), together with land abandonment, favour the occurrence of large forest fires. Nowadays, scrubland communities are the typical vegetation in the physiognomy and ecology of mountain areas in Portugal, leading to an entirely homogeneous landscape and repeated fires. Recurring fires, such as the ones that took place in the study area, have led to changes in vegetation and in the physicochemical properties of the soil, causing great socio-ecological damage (to private and public properties, infrastructures, landscapes, biodiversity, soil and water quality). In recent decades, exceptionally high rainfall events have created a greater potential for severe flooding and intense erosive processes. Soil affected by fire becomes much more susceptible to erosion, intensifying the movement of sediment into rivers, increasing the pollutants reaching the water supply systems and affecting fresh water quality. According to Shakesby (2011) a single intense rainstorm after forest fires can generate peak flows which produce 75% of the sediment eroded during a longer period.

In this context, this study confirms that the social–ecological system in the study area is extremely vulnerable. On the one hand, the characteristics of the population, namely the low population density, high proportion of elderly people and few young people, make these communities highly vulnerable. Having been less involved in forest fire management over the years, the loss of community skills has led to fuel accumulation, making forest fires uncontrollable if not suppressed immediately. Moreover, the delay in detecting fires and the difficulties in accessing the locations where fires tend to start due to the rugged topography, have also contributed towards this increased vulnerability. The isolation of these small villages, where human life and property are threatened, also represents a civil protection problem.

Government policies seem to be unable to control forest fires and their cascading effects, such as post-fire hydro-geomorphic processes. In Portugal, Mateus and Pereira (2014) state that this equilibrium is compromised by three problems, namely agency instability, lack of leadership in the form of overall system coordination, and a poor understanding of the interdependence of the fire prevention, fire pre-suppression and fire suppression axis. In addition, excessive year-to-year investment in fire suppression may mitigate fire damage in the short term, but in the long term may undermine preventative efforts, which become increasingly problematic as fuel accumulates. In years of extreme drought when there are many outbreaks of fires per day, as in 2005 and 2013, the state mechanism is unable to respond successfully to all cases and the local populations are not able to fight the fires as they did in the past.

In light of the above observations, disasters will continue to occur in the study area and in mountain regions, and will be equally or even more destructive than those that have occurred in the past. There is an obvious urgent need to strengthen and restore the resilience of mountain socio-ecological systems and their capacity to cope with severe hazards and environmental constraints, as the best option to prevent and mitigate natural risks.

Good governance should operate alongside an adequately defined programme of action that takes the existing risks into account. Land and forest management must be addressed in terms of cooperation and complementarily between agents (the government, the agencies responsible for fire prevention, fire pre-suppression and fire suppression, and the local population), favouring synergies that lead to communities that are better protected from fire and encourage sustainable forest ecosystems.

3.5 Limitations of the study and the need for further research

Despite the contributions provided by this study, certain limitations must be recognized, mainly relating to the methodology and research process. As the study area includes ungauged basins and given the scarcity of data, it is difficult to infer how a catchment area responds to input (rainfall), given the combined effects of several factors such as topography, geology, soil type, land use/cover, burnt area and fire severity.

Another gap in this research is due to an insufficient understanding of the impact of wildfires on the physical, chemical and biological properties of soil. These impacts depend heavily on fire intensity, duration and frequency. Recurring fires also affect the type of vegetation and the level of plant cover. All these variables are therefore essential to understanding the hydrological and erosional response on different scales.

Another interesting subject to explore is local residents' perceptions of the wildfire risk and how it increases the risk of flash flooding and debris flow. Assessing how local people deal with disasters, both individually and collectively, and assigning responsibility for post-wildfire and related disaster mitigation are other issues that should be addressed more comprehensively, requiring an interdisciplinary and holistic approach.

4 Conclusions

Although fire has been a tool used by humans for centuries and an important element in ecosystem dynamics, wildfires are nowadays a major concern in mountain regions in Portugal. In the study area, the recent fire history shows that both basins have been severely affected by large fires and several areas have been covered by fire one to five times. Taking into account the two most catastrophic events, in which most of the basin was affected by fire (1987 and 2005), landscape and ground conditions changed dramatically, leading to flash flooding and debris flows due to heavy rains, in both cases after one year.

Understanding fire frequency and the recurrence of intense hydro-geomorphic processes, and identifying some of the most important driving forces behind wildfires at the local level can contribute towards defining appropriate prevention measures, as well as providing support for the mitigation of post-fire consequences.

Significant social, economic, ecological, political and institutional changes, mainly in the second half of 20th century, have increased susceptibility to natural hazards and the vulnerability of people, property and the environment to natural disasters. In fact, the human and environmental dimensions in the study area (especially the high level of population ageing and the predominance of very flammable vegetation, together with the physical characteristics of the basins and the natural recurrence of heavy rainfall) exacerbate the impact of disasters, and vice versa, since disasters tend to amplify the impact on environmental and human factors. Thus, emphasising and reinforcing socio-ecological concerns in disaster management should become a major priority, requiring sound management of natural resources as a means of preventing disasters and lessening their impact on people, their homes, and livelihoods.

Given this context, it is imperative not only to implement measures aimed at reducing burnt areas, but also to develop methods and tools to identify and quantify the potential risks posed by flooding and debris flow as a result of fires, and to improve estimations of the magnitude and recurrence of these phenomena at river basin level.

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