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FIELD TRIP GUIDEBOOK

3rd International Meeting of Fire Effects on Soil Properties

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3rd International Meeting of Fire Effects on Soil Properties

Field Trip Guidebook

17th March, 2011

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Terra de Sonhos

Contents

Introduction

The present document is intended to be an auxiliary working instrument for the field trip to the northwest mountains of Portugal, organized during the 3rd International Meeting of Fire Effects on Soil Properties by the *Núcleo Investigação em Geografia e Planeamento da Universidade do Minho*, with the collaboration of the *Centro de Estudos de Geografia e Ordenamento do Território*, scheduled for March 15-19, 2011, in the city of *Guimarães (Portugal).*

The trip is programmed for 17 March 2011 and the proposed itinerary takes us on a tour of the beautiful and characteristic landscape of the Portuguese northwest. This occasion will allow us to discuss a series of issues associated with the theme of the conference: Fire Effects on Soil Properties.

Accordingly, we will begin the journey by examining the question of the influence of forest fires on the evolution of the Portuguese northwest landscape. Our attention will centre on the plant life dynamics throughout the last half century. More precisely, we will focus on how man has constructed and "deconstructed" the landscape, namely through its appropriation for economic activities and through man's influence on the occurrence of forest fires, either negligently or premeditated. This discussion is crucial in order to understand the evolution of the northwest landscape since the 1970s.

The second stop will bring us to the heart of the *Peneda-Gerês* National Park. This area was severely fustigated by forest fires in the summer of 2010. Here we will discuss the effects of the fires on the soil properties, as well as the cost-benefit of prescribed fires in the management of forest spaces and as an instrument of fire prevention and reduction.

Subsequently, we proceed to the mountain region of the *Serra da Cabreira*. This is the ideal place to understand the social factors and the assortment of inherent conflicts of interest involved in the forest fires of rural areas of the Portuguese interior.

The field trip will be led by a group of specialists on the themes of the conference, namely: António Bento Gonçalves (*Universidade do Minho*), António Vieira (*Universidade do Minho*), Flora Ferreira Leite (*Universidade do Minho*), Luciano Lourenço (*Universidade de Coimbra*), Hermínio Botelho (*Universidade de Trás-os-Montes e Alto Douro*), Artemio Cerdà (*Universidade de Valencia*), and Xavier Úbeda (*Universidade de Barcelona*).

Itinerary of the Field Trip

The mid-conference field trip which will begin at the *Universidade do Minho (Guimarães)* will travel through 5 municipalities (Figure 1), where we will visit the scorched areas of the summer of 2010 and an area that has been subject to a prescribed fire in February 2011. Lunch will be offered by the Municipality of *Vieira do Minho*.
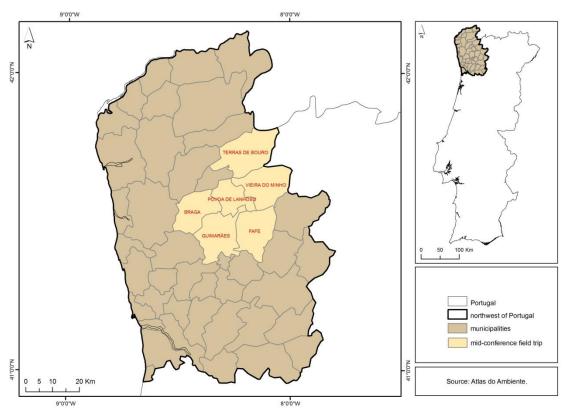

Figure 1 –Municipalities Visited in the in Field Trip

Accordingly, the more precise itinerary is:

> 8:30 – *Guimarães* (*Universidade do Minho*)
> 9:00 – *Braga*
> 9:30 – *S. Mamede de Penafiel* (Stop 1 – Landscape and forest fires)
> 10:30 – *S. Bento da Porta Aberta* (Coffee Break)
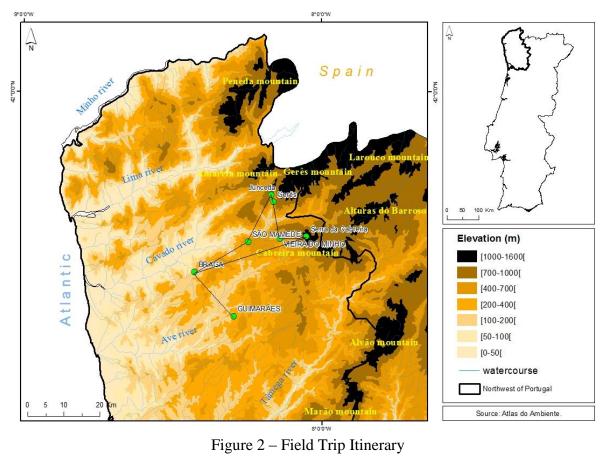> 11:15 – *Junceda* (Stop 2 – Prescribed fire)
> 12:45 – *Gerês*
> 13:30 – *Vieira do Minho* (Lunch)
> 15:30 – *Serra da Cabreira – Vale do Turio* (Stop 3 – Forest fires)
> 17:30 – *Braga*
> 18:00 – *Guimarães* (*Universidade do Minho*)

Figure 2 – Field Trip Itinerary

1. Geographic Characterization

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Geology

From a lithologic perspective, the principal rock formations in the Portuguese northwest are granites, quartzites, slates, and other related formations. Holocene (floodplain formations) and plio-pleistocene (fluvial terraces) cover formations are also present in this region (Figure 1).
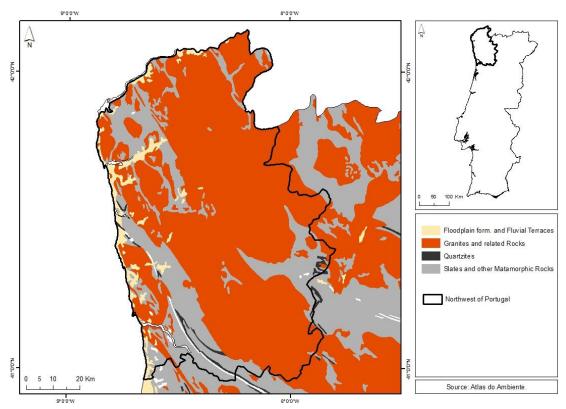
Figure 1 – Simplified Lithologic Map of the Portuguese Northwest

In the northwest the Hercynian orogenesis played a fundamental role in the regional geology. Most of the local granitoids, sin-orogenic, and late to post-orogenic granites are associated with the Hercynian cycle (N. FERREIRA *et al.*, 1987). However, "the existence of large fault scarps, sometimes exceeding 200 meters, either in the area of the *Peneda* and the *Gerês* or the area of *Monção* and *Arcos de Valdevez*, is sufficient proof that important tectonic movements occurred in the alpine cycle" (P. LEMA e F. REBELO, 1996).

11

The existing records on the tectonic evolution of the Portuguese territory during the Neogene and the Quaternary reveal that after a period of intense tectonic activity throughout the Miocene a calm period ensued afterwards during the Pliocene. Intense tectonic activity commenced again in the final phase of the Pliocene, continuing well into the Quaternary (Figure 2).
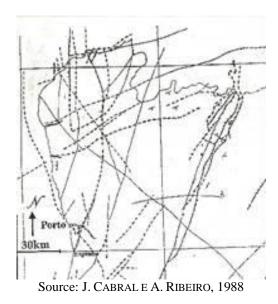

Source: J. CABRAL E A. RIBEIRO, 1988

Figure 2 – Part of the Neotectonic Map of Portugal

Relief

Besides being determined by the contemporary climate, the relief of the northwest still presents signs of past climates due to the great variability climatic conditions throughout its geologic history. However, geology and tectonics are the factors most responsible for the main characteristics of the regions relief.

The relief is scaled from West to East. In the proximities of the *Serra do Gerês* the relief is "lifted" from 0 to 1500 meters in less than 70 km. The main rivers of the region (*Minho*, *Lima*, *Cavado*, and *Ave*) present what P. B LEMA E F. REBELO (1996) designated as a "betic" orientation/direction (ENE – WSW) and are characterized by running through very wide and open valleys in the coastal areas and through very deep and narrow valleys in the mountain regions close to the coast.

As a result, it is not surprising that the most important mountains are separated by the deep valleys of the main rivers of the Portuguese northwest.

Climate

According to S. DAVEAU *et al*. (1985), the Portuguese northwest is characterized by fresh, wet winters cool winters and moderate to hot, dry summers. The average minimum temperature of the coldest month varies between 2 and 4ºC and negative temperatures are registered for 10/15 to 30 days a year. The highest average temperature of the warmest month varies between 23 and 32ºC. Temperatures over 25ºC are recorded between 20 to 120 days a year. According to the *Atlas do Ambiente* (1975) the average daily temperature varies between 12,5 and 15ºC.

Although the region exhibits Mediterranean features it is heavily influenced by the Atlantic. In effect, the climate reveals mild temperatures, with small thermal amplitudes, and

heavy average rainfall due to its geographic position, proximity to the Atlantic, and to the form and disposition of the main mountain ranges[1] which O. RIBEIRO (1986) designated as an "amphitheatre facing the sea".

As a result, the high volume of precipitation, which is unquestionably the dominant climatic trait of the Portuguese northwest, registers an average annual total of rainfall of over 1400 mm, although unevenly distributed throughout the regional. The magnitude of this phenomenon is due to the frequent passage of surface fronts associated with the influence of the proximity of the mountain system to the coastline ("moisture barrier").

Hydrography

As previously mentioned, the rivers expose the principal forms of the landscape. Accordingly, the *Minho* and *Lima* rivers are divided by the *Arga* (816 m), *Peneda* (1373 m), *Soajo* (1415 m), and *Castro Laboreiro* (1335 m) mountains; the *Lima* and *Cávado* rivers are separated by the *Amarela* (1361 m), *Gerês* (1548 m), and *Larouco* (1525 m) mountains; the *Cávado* and *Tâmega* Rivers are separated by the *Cabreira* (1261 m) and *Alturas do Barroso* (1279 m) mountains; and finally, the *Tâmega* and *Corgo* rivers are divided by *Alvão* mountain (1281 m) (Figure 3).
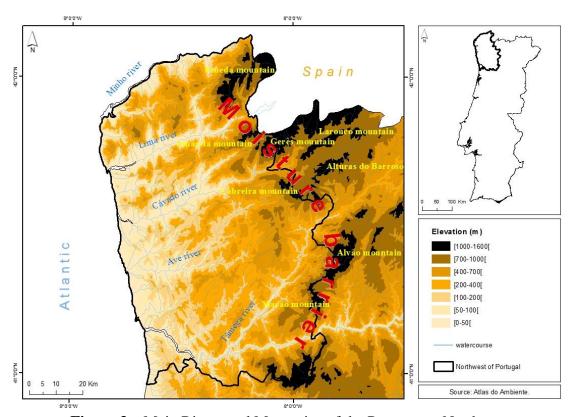
Figure 3 – Main Rivers and Mountains of the Portuguese Northwest.

The flow of the "Minho" region's rivers presents a distinguishing quality from the national perspective. Due to its climatic and geologic characteristics as well as its particular orography, the regional rivers have extraordinarily high stream flows. More precisely, the *Cávado* registers 38 l/s/Km^2 (*Barcelos*), the *Lima*, 31 l/s/Km^2 (*Ponte de Lima*), the *Ave*, 26

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[1] In the northwest, in a radius of 65 Km the average annual rainfall is 1374,2 mm in *Sto. Tirso*, at 28 m altitude, increasing to 1772,6 mm in *Fafe* at 330 m altitude and to 3071,1 mm in *Zebral*/*Serra da Cabreira* at 775 m altitude.

l/s/Km^2 (*Açude de Tougues*), and the *Minho*, 22 l/s/Km^2 (*Ponte de Felgueiras*) (S. DAVEAU, 1995).

Pedology

According to the Soil Map of Portugal, in the northwest region, there is a clear prevalence Cambisols which are moderately evolved and with a irregular fertility rates. Near the coast the Lithosols (incipiente soils, still developing due to rock degradation and rarely surpassing 10 cm in depth) are present, while the Rankers – i.e., shallow soils with reduced fertility – emerge in the higher altitudes.

Human Characterization

Regardless of the natural features of the region, human action (agriculture, pasture, silviculture, etc.) must be emphasized due to its profound influence in the regions physiognomy. To all intents and purposes, the prolonged activity of human beings in the region has contributed significantly to the degradation of the endogenous plant cover. Nevertheless, "even this human activity, particularly through the organization of the traditional agricultural systems, was dependent on the same physical factors that shape the natural systems" (P. T. GOMES e A. BOTELHO, 2004).
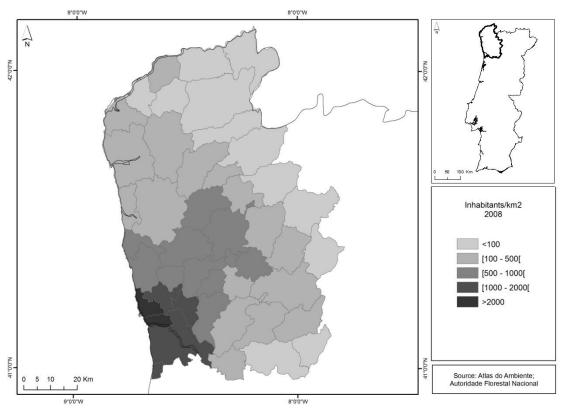

Figure 4 – Population Density by Municipality, for 2008, in the Portuguese northwest.

In effect, the Portuguese northwest has witnessed a significant demographic dynamic with high birth and nuptial rates.

The region has one of the densest concentrated populations in the Iberian Peninsula. Presently, the northwest has a demographic density that surpasses 360 inh./km^2 (369,1), a

value markedly superior to both the northern region of Portugal (175,1) and Portugal as a whole (112,9) (Figure 4)

Basic Landscape Units

The Portuguese northwest is a highly humanized region where the spatial organization reveals marked contrasts. However, this does not hinder the existence of a unitary ecologic system characterized by the physiognomy of the landscape, the group of species that inhabit it, and by the local adaptive strategies that differentiate the region from the rest of the country.

"Traditionally, two large biogeographic spaces in the Iberian Peninsula are identified. […] At our latitudes, the hydraulic regime is the principal factor responsible for the physiognomy of the landscape and the division between the dry and wet Iberia, the climatic types (atlanticity as opposed to mediterraneaty), and the large phyto-corologic regions (Euro-siberian and Mediterranean) testify to this great division of the Peninsula" (P. GOMES e A. BOTELHO, 2004). It this context, the Portuguese northwest is part of the Euro-siberian region.

The referred to climatic characteristics are responsible for determining the local vegetation. With a minor summer aridity, in which the number of dry months rarely surpasses two, natural vegetation is typically evergreen, resistant to drought and fire-prone. Ecologically, the Portuguese northwest, with its climatic characteristics that directly influence the type of endogenous plant communities, is situated in the humid Iberia and distinguishes itself from the rest of the country.

Some plant species from middle Europe have the meridianal limit of their expansion in the North of Portugal, where some of their most important settlements are located. This fact is due to the affect of the ocean which attenuates the heat and dryness of the summer months by conditioning abundant rainfall.

As a fundamental element of the landscape, the vegetation is an excellent testimony to the orographic and edafo-climatic conditions of a region as well as to the anthropic action.

Biogeographically, the Portuguese northwest is located in the Miniense Subsector and the Geresiano-Queixense[2] subsector (RIVAS-MARTINEZ, 1996), allowing for a correspondence between the *Minho* Lowlands and the transition described by O. RIBEIRO (1970, 1991) between the mentioned Lowlands and the *Trás-os-Montes* Highlands.

The Miniense Subsector is essentially a granite dominated area that is progressively corrugated as we head inwards. It presents a tempered hiper-oceanic or oceanic bioclimate, mainly positioned in the termo-temperate and meso-temperate belt, with a humid to hyper-humid ombroclimate. […] The climactic vegetation is constituted by Gallic-Portuguese Alvarinho Oaks (*Quercus robur* L.) which survive in small, highly threatened pockets (J. C. COSTA *et al*, 1998).

From a biographic perspective, the Miniense Subsector corresponds to the Minho Lowlands (O. RIBEIRO, 1970, 1991), whose essential features are the dispersed and disseminated settlements in which the dwellings share a close relationship with the cultivated land and the landscape is highly compartmentalized due to the plethora of small estates which are fenced off by small port trees and bushes or vines in *ramada*. In the slopes with poorer and less irrigated soils we can find forests composed of a mixture of Maritime Pine Trees (*Pinus pinaster* Aiton.) and Eucalyptuses (*Eucalyptus globulus* Labill) with the manifestation of some spontaneous oaks and other corresponding fagaceas trees[3].

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[2] Both belong to the Gallic-Portuguese Sector, Sub-provincial Gallic-Asturiana, Provincial Cantabro Atlantic, Sub-provincial Atlantic, Sub-region Atlantic-Mideuropean, the Euro-Siberian region.

[3] At the moment, forest fires and the changes in agricultural practices (due to social changes) altered significantly this setting, giving rise to large areas of shrubland instead of Pine Trees and vineyards, and orchards instead of the *ramadas* and corn fields.

The Geresiano-Queixense Subsector has a highly irregular relief where the hercynian granites are largely prevalent. It is situated in the supra-temperate belt (Montano) with a hyper-humid (humid) ombroclimate according to its exposure in the altitudes above 600-800 m. The climactic vegetation is composed of Alvarinho Oaks (*Quercus robur* L.) in the more oceanic and hyper-humid areas or Pyrenean Oaks (*Quercus pyrenaica* Wild.) in the areas with a humid ombroclimate or in the higher and continental biotypes (J. C. Costa *et al*, 1998).

Biogeographically, the Geresiano-Queixense Subsector also corresponds to the transition between the Lowlands and the Highlands. Here we can verify a gradual shift in which the pine tree is substituted by Alvarinho Oaks (*Quercus robur* L.) and Birch Trees (*Betula alba* L) and low creeping shrubbery (O. Ribeiro, 1991) in the slopes due to the increase in altitude (colder and with more rainfall in the humid season).

In summary and considering the basic landscaped units, we can distinguish six different basic spatial uses in the Portuguese northwest (P. Gomes, 2001): the plain agricultural systems which comprise the lowland landscapes with dispersed settlements; the mountain agricultural systems in which the settlements are clustered; the urbanized systems, with its cities and towns; the uncultivated systems, composed primarily of more or less degredated shrubbery and bare or exposed rock; planted forests with a predominance of Maritime Pine Trees (*Pinus pinaster* Aiton.) and Eucalyptuses (*Eucalyptus globulus* Labill); deciduous forests, dominated by Alvarinho Oaks (*Quercus robur* L.) and Pyrenean Oaks (*Quercus pyrenaica* Wild.) which correspond to spontaneous or sub-spontaneous areas.

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2. Mountain wild spaces in Portuguese northwest

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The influence that the climate and the relief exercise over the physical milieu is also determinant to the basic units of the landscape systems; forests, shrublands, agricultural zones, and urbanized structures (Figure 1).
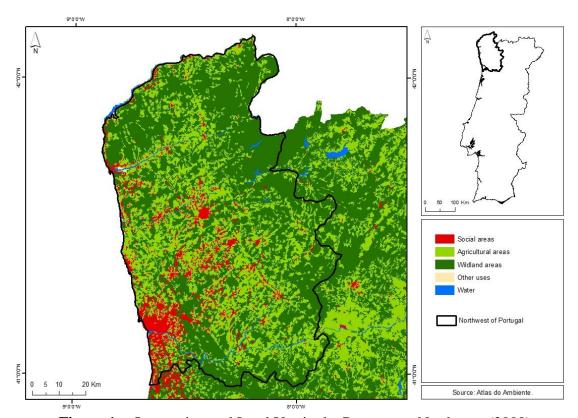

Figure 1 – Occupation and Land Use in the Portuguese Northwest (2000)

As regards to the forests, the areas most affected by the influence of the Atlantic are the most productive due to the shorter duration and intensity of the aridness of the summer season. It is in this area that the more noble species, such as the Alvarinho Oaks (*Quercus robur* L.) or the Sycamore (*Acer pseudoplatanus L.*), and the Maritime Pine and the Eucalyptus presently find the best growth conditions (A. V. CORREIA E A. C. OLIVEIRA, 2003).

As a result, the Portuguese northwest has excellent natural conditions for afforestation. The only limiting factors are related to altitude where the inauspicious topography and the lower temperatures can impose some restrictions[4].

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[4] The Portuguese northwest can be divided into four Great Afforestation Regions: Atlantic Basal Zone (zone of highly productive forests, the "manor of the Alvarinho Oak" is home of species like the maritime pine, the

The afforestation that led to the present forest areas was initiated in the 20th Century in accordance in the Forest Regime (1901 to 1905) and the establishment of the 1938 Afforestation Plan (BENTO GONÇALVES, 2006).

It was in this context that the woods and forest perimeters in the mountains of the northwest were "born" (Figure 2)
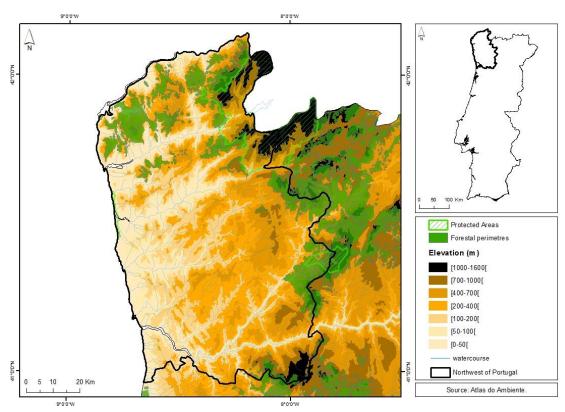

Figure 2 – Forest Perimeters and Protected Areas in the Portuguese Northwest

The establishment of protected areas[5] in Portugal remotes back to the 1970s (Law n. º 9/70 of 19 June), but is also related to the 1938 Law of Forest Settlements since this document was the first national regulation to foresee protected areas in the modern sense of the term.

In the northwest region we should highlight the *Peneda-Gerês* National Park, established by the Law n. 187/71 of 8 May, which is the only national protected area with a statute of National park, acknowledged by the International Union for Conservation of Nature (IUCN) (Figure 5).

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monterrey pine and the eucalyptus; Sub-Atlantic Sub-mountain Zone (Zone with typical forest characteristics with great aptitude for various species); Sub-Atlantic Mountain Zone (typical forest zone where the oak and chestnut trees encounter excellent conditions to grow. In higher altitudes, due to the restrictions to the expansion of some specie, the maritime pine may be substituted by exotic resinous species. In the highland plateaus with sylvan-pastoral conditions, the forest species play a fundamental role in the compartmentalization and other solutions of pasture under cover); and Altimontana Zone (where the altitude imposes great limitations to forest expansion) (A. V. CORREIA E A. C. OLIVEIRA, 2003).

[5] Protected Areas: "territorial areas and interior and maritime bodies of water in which the fauna, the flora, the landscape, the ecosystems or other natural occurrences present, due to their rarity, ecologic or landscape value, a scientific, cultural or social importance and relevance that merit special specific measures for the conservation and management of the natural resources in order to promote the rational management of the resources and promote the natural and cultural heritage, through the regulation of the artificial interventions that may cause them harm" (Law 19/93, of 23 January).

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3. Forest Fires in Portugal

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Since the last quarter century forest fires have registered a significant increase in both the number of occurrences and size of the scorched areas. This phenomenon is due mainly to the profound social changes that began to be felt in the population residing in the forest areas, especially in the Portuguese interior, since the second half of the twentieth century.

These social changes began with the industrialization of the Setúbal Peninsula. This industrialization process attracted vast amounts of manpower to the Greater Lisbon Area. Also the subsequent surge of emigration to the Central European countries (France, Germany, Luxembourg, Switzerland, ...), led to a substantial reduction in the workforce living in the forest areas - or areas apt for forest development - causing major changes in the population that remained there.

These changes affected not only the demographic, social, economic, and cultural structure of the population residing in these areas, but also the sectors of activity. There was a significant reduction in the primary sector, particularly in the agro-forestry-pastoral activities which were most associated with the agricultural activities with direct intervention in the forest. In contrast there was a significant increase in the activities associated with the industrial and service sectors, in accordance with what occurred in the wider Mediterranean areas of southern Europe.

Such an unfavourable social situation was already present in the late 1970s. At that time processes of depopulation and aging of the rural population were already visible. These processes led not only to the decline in the rural labour-intensive workforce, but also to an increase in wages due their shortage. This, in turn, led to a number of other consequences that, however, cannot be dissociated from a set of external factors that also encouraged it.

Of these other consequences, at least two should be highlighted. First, the gradual extinction of the practice of collecting scrublands for animals, due to an easier access to artificial fertilizers, which thus came to replace traditional manure. Second, the reduction of firewood consumption, which resulted from electrification and the increasing use of the gas cylinder. These two factors together contributed to the gradual and continuous increase of the biomass available in the forests (L. Lourenço, 2006a, p. 63).

Equally significant, the small size of the property structure, coupled with the poor management of the forest areas, were factors that hampered the defence against forest fires and exacerbated the devaluation of the social, economic, and environmental usefulness of the forest and areas apt for forest activities and consequently to increase the fuel load in the forests.

Finally, in result of not only these but other circumstances, the increasing rise of the fire risk, along with the intensification of the loss of competitiveness and attractiveness for investments in forestry activities, although with some exceptions, led to the abandonment of forest spaces due to its low economic value, increased phytosanitary problems, and higher exposition to the risk of forest fires (L. Lourenço et al., 2006, p. 5).

Thus, the rural exodus has led to the concentration of the active population in large urban areas and district capitals, and left the forest areas with a very elderly population. On the other hand, the rapid change in the occupation of the active population that continues to

live in the forest areas and is now occupied in activities primarily in the secondary and tertiary sectors, also contribute to the abandonment of many agricultural fields.

Therefore, not only were many areas of uncultivated land gradually occupied by scrubland and forest, thus increasing significantly the spaces apt for forest activities,, but also, and concurrently, intervention in the forest diminished leading to the accumulation large fuel loads.

Accordingly, those situations that apparently seem to have nothing to do with forest fires, which we have designated as indirect causes (L. Lourenço, 1995, p. 178), are not only the main factors responsible for the existence of large forest fires, but are also the most difficult to eliminate.

In fact, by creating conditions that subsequently interfere directly in the behaviour of fires by facilitating the progression of the flame fronts and, therefore, the rapid development of the fires, they thus contribute indirectly to larger scorched areas.
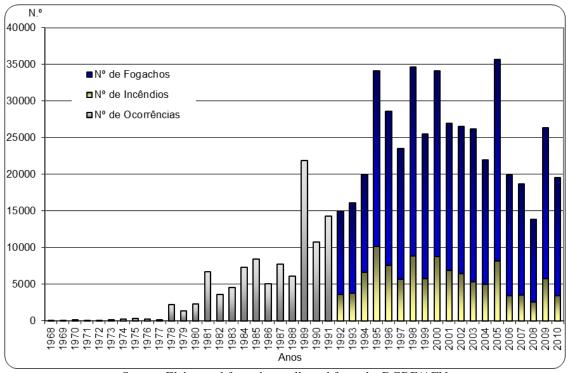
Temporal Evolution

The tremendous increase in the exponential trend of the number of occurrences of forest fires verified since the end of last century should lead to a more serious and responsible analysis of the problem and subsequent implementation of concrete measures aimed at substantially reducing the number of occurrences.

To our knowledge, this hasn't been done and therefore, as the result of specific actions and circumstances, this trend fortunately seems to have started to reverse since the beginning of the present century - assuming that 2005 was an anomalous year just as the fires of 1989, 1995, 1996, 1998 and 2000 were. However 2009 and 2010 make us believe that this downward trend will not be as sharp as it might have initially seemed (Figure 1), especially since 2007 and 2008 were, from a meteorological point of view, unfavourable to the occurrence of ignitions and the development of large forest fires (Figure 2) - as the fires of 1997, 1988 and 1977 also were.

Accordingly, the temporal trend followed by these two variables - i.e., number of occurrences and scorched areas - is completely different. The number of occurrences is closely associated with human causes (either intentional or negligent), which result from different behaviours and attitudes that have long been identified and that need changing. The extent of the scorched areas, for its part, is directly linked to the different weather conditions throughout the years, the lack of land and forest management, and, finally, to some inefficiencies in the fire fighting operations.

Thus, on the one hand, if the sharp rise in the number of occurrences recorded in the late 1970s and early 1980s were mainly associated with the change in the methods of statistical summary data, the progressive increase verified over the 1990s cannot be due solely to the generalization of a more rigorous treatment of the statistical information. In fact, since 1989 (with special reference to 1995, 1998, and 2000), values have been absolutely abnormal. These cannot be attributed only to the increment of greater statistical accuracy or to the favourable weather conditions for ignition, especially since they are not decisive for the explanation of number occurrences, as was demonstrated with what happened in 1991, with far fewer events than 1989.

Source: Elaborated from data collected from the DGRF/AFN

Figure 1 – Evolution of the Annual Number of Occurrences of Forest Fire in Mainland Portugal.

Source: Elaborated from data collected from the DGRF/AFN
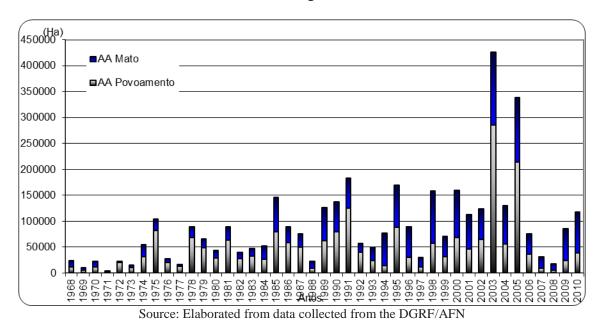
Figure 2 – Annual Evolution of the scorched areas in Mainland Portugal.

On the other hand, in terms of scorched area, the values verified in 1977, 1988, and 1997 were due to unfavourable weather conditions which facilitated ignition and the spread of forest fires. However, the disasters of 2003 and 2005,cannot be explained only by the negative weather conditions. The fires of 2003 cannot be attributed only and exclusively to the heat wave of late July and early August, and the lightning discharged by dry

thunderstorms on 01 and 02 August, 2003. Similarly, the fires of 2005 may not be entirely attributed to the drought of that same year.

There is no doubt that these aspects were important. But the state of an almost total abandonment of the woodlands accompanied by the lack of adequate planning and supervision (L. Lourenço, 2006b, p. 73), and coordination of the fire fighting efforts were decisive. The fire fighting initiatives also suffered from a lack of overall efficiency that results from of the absence of training and the use of inappropriate equipment, to name just a few of the most flagrant and frequent deficiencies.

In addition, contrasting with the slow evolution of forest cover growth over the centuries, recent years have demonstrated very rapid changes, mainly due to the high incidence of forest fires, which resulted, among other things, in a profound change of the species, particularly of the autochthonous species.

At present, the two most representative species of forests in northern and central Portugal are the pine and eucalyptus forests (Table I), whereas previously, oak and chestnut tress were predominant..

TABLE I – Area Occupied by the Most Representative Species in the Portuguese Forests

Forest Species	Forest Aea	
	Hectares (ha)	Percentage (%)
Maritime Pine (*Pinus pinaster*)	976 069	31
Eucalypts (*Eucalyptus spp.*)	672 149	21
Cork Oak (*Quercus suber*)	712 813	22
Holm Oak(*Quercus rotundifolia*)	461 577	14
Other Resinous Tress	105 008	4
Other leafy trees	273 515	8
Total	*3 201 131*	*100,0*

Source:DGF/IFN, 2001

Although the holm and the cork oak still continue to dominate, eucalyptus and pine trees began to gain ground rapidly and occupy an increasingly significant areas. This transformation has also contributed to the increase in the number of occurrences, and especially, in recent years, to the large fires south of the Tagus River and in particular in the hills of the Algarve region.
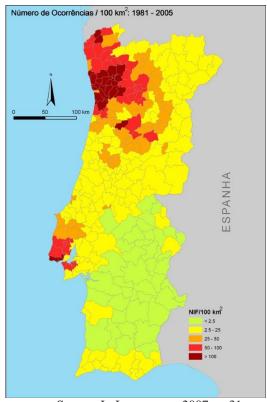

Spatial Distribution

Similarly to the temporal distribution of the number of occurrences in which the scorched areas reveal different behaviours, the spatial distribution also reveals particular patterns of dispersion.

Thus, a comparative analysis of the average values shows a concentration of the number of occurrences in the municipalities along the coast and in particular around the major urban centres in Porto in northern Portugal - sprawling across half-concentric circles that will dissipate northwards to Braga, southwards to Aveiro, and inwards to Vila Real and Viseu - and Lisbon, in the Centre and Southertn regions, although with minor importance in this case (Figure 3).
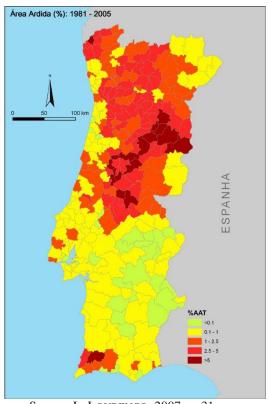
In turn, the municipalities that registered the highest value of scorched areas are located in the mountainous areas, especially in the interior of central and northern Portugal. Therefore, the areas most affected by fires covered virtually all of the central and northern

municipalities (though less so on the coast and some of the '*raia*'), near the Spanish border (with particular focus on those developing along the *Cordilhera Central*), and in the South, in *Serra de Monchique* (Figure 4)

Source: L. LOURENÇO, 2007, p. 31

Figure 3 – Geographic distribution of the average number of occurrences of forest fires per 100 km^2 in each municipality of mainland Portugal for the period 1981 - 2005.

Source: L. LOURENÇO, 2007, p. 31

Figure 4 – Geographic distribution of the average of scorched areas by percentage in each municipality of mainland Portugal for the period 1981 - 2005

The Critical Years: 2003 maximum of scorched area and 2005 maximum of the number of occurrences.

The maximum values for the forest fires in these two years – i.e., the scorched areas in 2003 and occurrences in 2005 - cannot be attributed solely to weather conditions, although they were both favourable to the ignition and spread of wildfires. These conditions have long been known and are related to high air temperature and low relative humidity (L. Lourenço, 1988, p. 262) and wind speed, preferably from the east quadrant, particularly when it is manifested through strong gusts (L. Lourenço, 1996, p. 59). These weather conditions are usually present during the most critical forest fires. Recent years have testified to the frequency of these conditions over the past couple of years and are not a new phenomena.

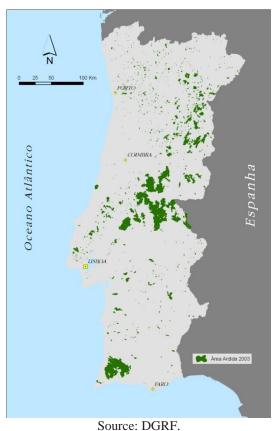In fact, as previously underlined (L. Lourenço, 2007), 2003 distinguished itself for recording an unusually high number of dry thunderstorms, with a remarkable discharge of lightning responsible for a substantial part of the high number of fire start-ups observed. However it should be stressed that on a weekly basis this value was always lower than the maximum weekly value recorded in the five preceding years.

From the meteorological point of view it is worth noting that 2003 was a year that registered cooler and more humid conditions than some of the previous years, particularly in traditionally problematic areas of the Central and Northern coast, or maintained weather conditions similar to those in the harshest years, particularly in late July and early August.

In contrast, in the hinterland, especially in Central and Southern Portugal, the situations were generally more severe than those usually recorded, so it was in these areas that the large scorched areas were mainly concentrated (Figure 5).

However, in the most critical period of the fires, corresponding to the first days of August, we must recognize that the simultaneity of many fires, due to an impressive amount of sparks from dry thunderstorms, created the conditions for the flames to spread easily and increased the difficulty of the fire fighting operations, which also contributed to the manifestation of a certain "collective hysteria" which in part resulted from the highlight given to the subject by the media.

Moreover, the weather conditions in certain regions of mainland Portugal were without a doubt highly conducive to the development of the fires due to a major heat wave that occurred between July 29 and August 14, 2003. This period registered a high number of consecutive days with very high values for both the maximum and minimum air temperature and with low values for the relative humidity, which were particularly low in the countryside registering values under 20%.

Source: DGRF.

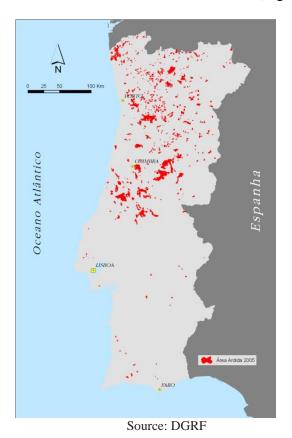**Figure 5** – Scorched Area in Mainland Portugal in 2003.

On the other hand, the values of the air temperature were above 30 ° C which, combined with the relative humidity under 30%, corresponded to situations of high forest fire risk, as has been the case over the years (L. Lourenço, 1991). From this viewpoint, one can not consider that the year has been abnormal.

However, the persistence of very high temperatures and very low values of relative humidity had a significant impact on the number of occurrences and the size of the scorched areas. The situation was so severe that a state of public calamity was decreed.

Thus, the balance for 2003 could not have been worse in terms of forest fires. In fact, in 2003, 12 of the 20 largest wildfires on record and 8 of the 10 major fires that have occurred in Portugal so far were recorded.

In turn, in 2005 the values of the scorched areas were once again much higher than those of the previous years, so it scores second in the ranking (Figure 2). But besides that, 2005 was notable mainly because it countered the tendency for reducing the number of occurrences In fact, 2005 reached the maximum value recorded (Figure 1).

Accordingly, in terms of spatial distribution of scorched areas, 2005 was different from 2003, but resumed the traditional spatial patterns: the largest scorched patches returned to the central and northern regions of Portugal (Figure 6), and the largest number of occurrences were near the urban centres (Figure 7).

Source: DGRF

Source: DGRF

Figure 6 – Scorched areas in mainland Portugal in 2005

Figure 7 – Occurrences in mainland Portugal in 2005

It is obvious that large forest fires depend on numerous factors and constraints which we will not enumerate here. But, if weather conditions are one of the conditionalisms, we must insist on the importance of the management of forest spaces, without which it will be impossible to reduce the frequency and the magnitude of forest fires. The distribution maps for 2005 clearly indicate the areas where interventions should be prioritized.

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4. Forest Fires in the Portuguese northwest

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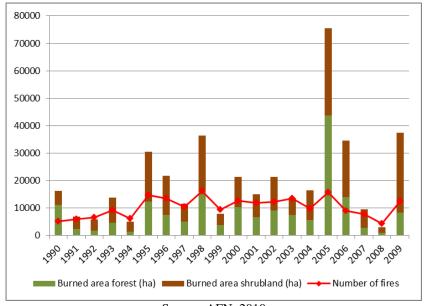Guimarães (Portugal)
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The number of occurrences of forest fires and the scorched areas in the Portuguese northwest is remarkably high. In the period from 1990 to 2009 there were a total of 206423 occurrences, representing 43,7% of the total occurrences on the national level. However, in relation to the area scorched by forest fires the same period registered a total of 387395 hectares, which represented only 16,01% of the total area scorched in the whole of the Portuguese territory for the period under consideration (Table I and Figure 1).

TABLE I – Historical record of the number of forest fires occurrences and scorched areas (hectares) in the Portuguese northwest in the period of 1990 – 2009

Year	Number of fires	Scorched forest area (ha)	Scorched Shrubland área (ha)	Total Scorched area (ha)
1990	5049	11219	5062	16281
1991	5867	2434	4461	6895
1992	6476	1753	4047	5800
1993	9179	4689	9013	13702
1994	6207	1329	3623	4952
1995	14657	12307	18263	30570
1996	13489	7380	14394	21774
1997	10394	5087	6530	11617
1998	16136	16482	19851	36333
1999	9492	3871	4069	7940
2000	12667	10245	11162	21407
2001	11947	6671	8405	15076
2002	12228	9191	12225	21416
2003	13465	7462	6204	13666
2004	9760	5601	10773	16374
2005	15688	43663	31869	75532
2006	9025	13940	20705	34645
2007	7772	2882	6605	9487
2008	4394	1009	1946	2955
2009	12531	8245	29218	37463
Total	**206423**	**175460**	**228425**	**403885**

Source: AFN, 2010

Figure 1 – Evolution of the annual number of forest fire occurrences and total scorched area in the Portuguese Northwest in the period of 1990 – 2009

Just as was case in the national context, the years of 1998 and 2005 registered the highest number of occurrences in the northwest region, with 16136 and 15688 respectively. The reduction of occurrences in the years between 2005 and 2008 (presenting the lowest value in the 19 year period under analysis) are worth signalling. This tendency was inverted in 2009. Nevertheless, we can confirm a tendency, though slightly attenuated (R^2=5,8%) for the rise in the number of occurrences (Figure 2).
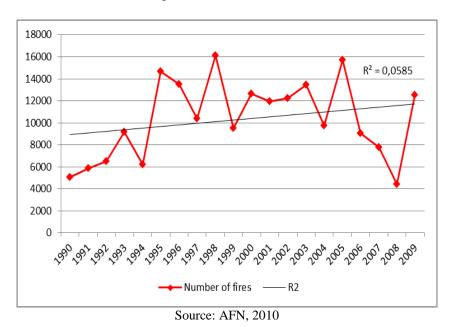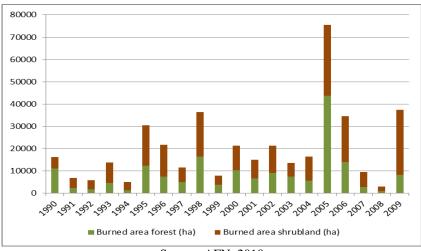
Figure 2 – Evolution of the annual number of forest fire occurrences and tendency line for the Portuguese northwest for the period of 1990 - 2009

Regarding the area scorched in the northwest region, the years 1998, 2005, 2006, and 2009 registered higher values and it is interesting to note that while 2003 had the highest

value at the national level, in regional terms it presented a rather diminished area. For the northwest 2005 witnessed the largest area scorched. 2008 stands out as the lowest value for this time series (Figure 3).

Source: AFN, 2010

Figure 3 – Evolution of the total scorched area (ha) in the Portuguese northwest for the period 1990-2008

The area of the settlements scorched annually is marked by annual variations which vary from a minimum of 1009 ha (in the year 2008) to a maximum of 43663 ha (in 2005). The year 2005 is an exception since it recorded unusually high values for the region (Figure 4).

Source: AFN, 2010

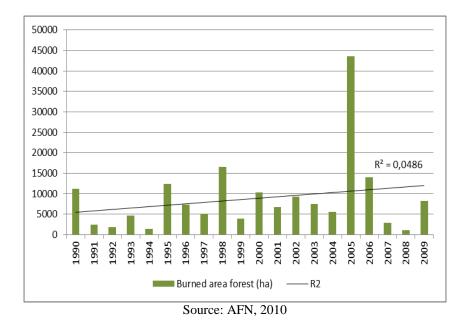**Figure 4** – Evolution of the scorched areas of settlements (ha) and tendency line for the Portuguese northwest for the period 1990-2009

By analyzing the tendency line we can observe the existence of a positive correlation between the scorched settlement areas and the temporal evolution. More precisely, we can verify a tendency for augmentation of the scorched areas in the long run. However, the square

of the correlation coefficient (R^2) indicates that only 4,86% of that growth can be correlated with the temporal evolution (Figure 4).

The area of shrubland scorched anally varies considerably. The lowest value was 1946 ha in 2008, which contrasted to the 31869 ha of 2005. Since 1993, only fiver years lowered under 500 ha (1991, 1992, 1994, 1999, and 2008). 2005 registered the highest value in the series with 31869 ha, while 2008 revealed the lowest value with 1946 ha. There is also a tendency for the area of shrubland scorched to augment over time. The correlation between the temporal evolution and the referred to scorched areas (R^2) is 17,09% (Figure 5).
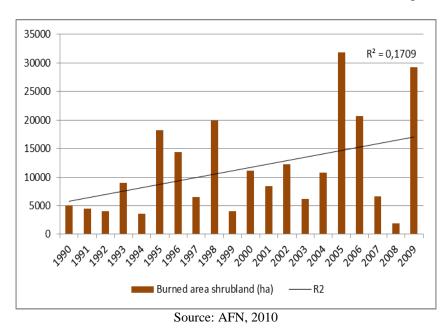

Source: AFN, 2010

Figure 5 – Evolution of the scorched area of shrublands (ha) and tendency line in the Portuguese northwest for the period 1990-2009

In summary, an annual variability of the scorched areas (settlements and shrublands) is verified. Equally, the forest fires also display an annual variability. Nevertheless, there is a tendency in the long run for a rise in the scorched areas and number of occurrences.

The value of the scorched areas and the number of occurrences of a particular year do not seem to influence the value of the following year (APIF/ISA, 2005). This estocastic behaviour can be explained in part by the variability of the meteorologic conditions of the summer season.

The geographic distribution of the forest fires in the Portuguese northwest is não even. The number of occurrences is higher in the more urban municipalities. There is a positive correlation between the number of occurrences and the number of inhabitants (APIF/ISA, 2005).

The distribution of the scorched areas in the northwest is also charactized by a accentuated difference between the coastal and central municipalities and the more interior municipalities. This distinction is evident when we analyze the maps of the scorched areas of the region for the period between 1990 and 2009[6] (Figure 6). Here we can verify that the more interior, mountainous municipalities, with their demographic debilities and the predominance of forest areas over the other land uses (Figure 1, 2.Mountain wild spaces in Portuguese northwest), present more extensive scorched areas, contrary to the distribution pattern of the forest fire occurrences.

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[6] Information provided in *shapefile* format for Arcview by AFN.

Source: AFN, 2010
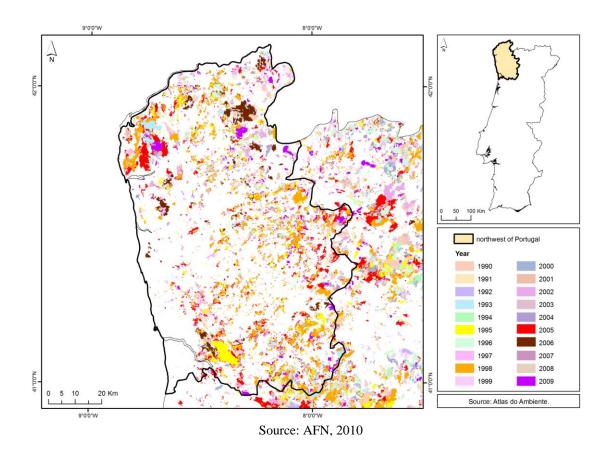
Figure 6 – Scorched area per year in the Portuguese northwest for the period 1990-2009

The geographic distribution of scorched areas per municipality in the northwest reveals the vulnerability of the mountain municipalities. The municipalities covered by the "moisture barrier", deserve special mention (Figure 3, 1.Geographic Characterization, Hydrography)

The climate also significantly affects the quantity and type of plant life in each region. The seasonal dynamics, with its percentage of humidity, indirectly influences the occurrence of forest fires and their propagation (PYNE *et al*., 1996). This implies that the high volume of rainfall in the northwest – with an annual average of over 2000 mm – is na important factor in the production of biomass (Table I1)

Table II – Rain stations located in the Cabreira Mountain, in the municipality of Vieira do Minho (1961-1990)

Rain station	Average annual rainfall R (mm)	Station altitude (meters)
Brancelhe	2118,7	380
Guilhofrei	2705,7	350
Salamonde	2281,9	550
Zebral	3071,1	775

Source: IMNG

The high level of rainfall is unquestionably the most outstanding climatic characteristic of the northwest region. It contributes to the great level of productivity of

biomass of the region and, consequently, making the municipalities with the larger forest areas (generally the more mountainous) more vulnerable to the progression of fires.

The demographic situation of the northwest has an incontestable direct influence in the "forest protection" in that the aging population in the rural areas and the concentration in the main urban centres contribute to significant spatial imbalances. This implies an abandonment of the agricultural areas and forests in the interior areas with the consequent lack of management of these spaces and the growth of the combustible load (PNDFCI, 2005). Due to this reality and to a climate the auspicious to the production of biomass, the shrub layer spilled over into the agricultural fields transforming them in shrublands which then are dominated by forest spaces that are more vulnerable to the occurrence of forest fires (LOURENÇO, 2006).

As a result, the high production of biomass, the abandonment of the rural space, and, in particular, the mountain areas with their inherent problems and physical and social disadvantages (BENTO GONÇALVES 2006), generate conditions which are favorable to the rapid propagation/progression of forest fires. More precisely, the mountain areas are subject to a plethora of conflicts that result from a series of opposing interests – e.g., land use, coexistence between the rural life and urban visitors, cattle grazing and property rights, hunting, etc. – which make fighting fires more difficult and contribute to the extension of the scorched areas (BENTO GONÇALVES *et al*., 2009).

The reincidence of fires in the same places is, in part, also due to the aspects above.

The maps on the spatial distribution of the reincidence of scorched areas in the Portuguese northwest for the period 1990-2008 confirms the high vulnerability of some of these spaces to forest fires (Figure 7).
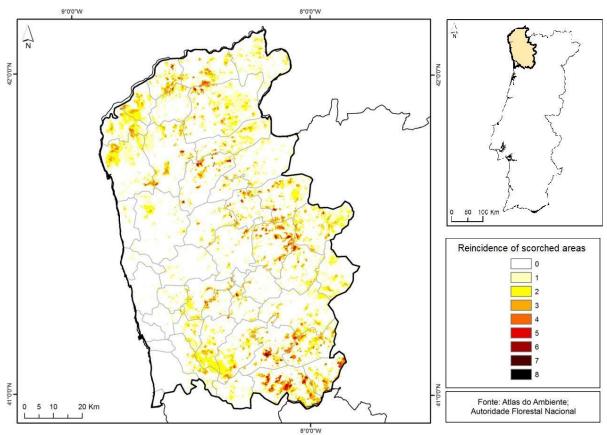

Figure 7 – Reincidence of scorched areas in the Portuguese northwest in the period 1990-2008

We can verify that this region presents areas with a level of maximum incidences equal to that registered for the national level (8).

Of the total area of the northwest (785565,7 ha), 222648,5 ha, representing 28,3% of the region, have been scorched at least once. Of those spaces (222648,5 ha), 15,4%, corresponding to 121452,1 he were scorched only once. 8,2% of the total scorched area in the northwest were scorched only twice and 3,1% were scorched at least three times. The areas scorched more than three times are very few. Records show that areas scorched residual values for areas scorched four (1,1%), five (0,45), six (0,08%), seven (0,01%), and even eight times (0,002%) (TABLE III e IV)
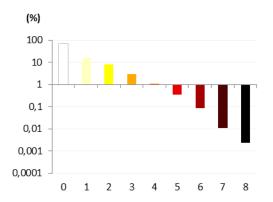
TABLE III - Scorched Area (ha) and percentage of scorched area in relation to the total area of the Portuguese Northwest in the period 1990-2008

	Scorched Area (ha)	Scorched Area /Total Area (%)
Total Area Scorched	222648,5	28,3
Non-scorched Area	562917,2	71,7
Total Area	**785565,7**	**100**

TABLE IV – Scorched Area (ha) and percentage of scorched area in relation to the total area of the Portuguese northwest in accordance with the number of times scorches in the period 1990 – 2008

Scorched Area (N. of Times)	Scorched Area (ha)	Scorched Area / Total Area (%)	Scorched Area/ Total Scorched Area (%)
Only Once	121452,1	15,4	54,5
Only Twice	64540,4	8,2	29,0
Only Three Times	24302,2	3,1	11,0
Only Four Times	8832,1	1,1	4,0
Only Five Times	2758,4	0,4	1,2
Only Six Times	659,8	0,08	0,3
Only Seven Times	85,4	0,01	0,04
Only Eight Times	18,1	0,002	0,008
Total	**222648,5**	**28,3**	**100**

While comparing the distribution of the area of the Portuguese northwest with the area of Portugal, in terms of the degree of forest fire incidences, we can verify that the total area of scorched land is higher in the northwest (28,3%/19,6%). The same hold true for the area effected by a fist incidence – i.e., 15,4% in the northwest and 14,4% in Portugal. It is after the first incidence that we can verify greater differences. In fact, the northwest registers, in percentage, a higher number value of scorched areas for the higher degrees of incidence. It is noteworthy to highlight the fact that the percentage of areas scorched eight times registers a value of 0,002%, in the northwest in comparison to the national value of 0,0002% (Figures 8 and 9).
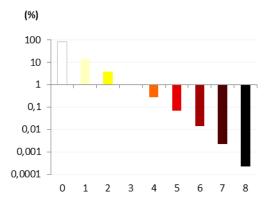
Figure 8 – Distribution of the area of the Portuguese northwest (%) by degree of forest fire incidences in the period 1990-2008

Figure 9 - Distribution of the area of the Portuguese mainland (%) by degree of forest fire incidences in the period 1990-2008

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5. Prescribed burning in Portugal

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Wildland fire is as old as terrestrial vegetation, and has shaped our landscapes, as well as our cultural evolution. However, the development of fire use as a technique anchored in science is recent.

The use of fire in forest management in Portugal was firstly documented by Frederico Varnhagen in a handbook written in 1836. This forest officer wrote a burning prescription for the coastal pine plantations in Central Portugal, which remains qualitatively valid:

"*After a pine stand is 20 years old there is a safe way to prevent it from being burned by summer wildfires: burning the litter in dry winter days will not damage the roots, and if the operation is repeated annually there will be no danger of wildfires ... The pine stands that get used to have their floor burned grow much faster and the benefit is great in every sense ... It is obvious that for a safe operation, even in wintertime, the forest should not have tall shrubs in the understory… The burn must be done with appropriate winds, and fire should be lit on the opposite side of the wind*".

This pioneer testimony was ignored, but traditional fire use has persisted in our rural communities as a land management tool. Occupational burning to manage rangelands and habitas was learned by the new generations from their ancestors. Prescribed burning has been developed by foresters in the U.S. and Australia since the 1950s and was introduced in Portugal in the mid 1970s, after the visits made to the Peneda-Gerês National Park by Edwin Komarek, a fire ecologist from the U.S. Tall Timbers Research Station, invited by José Moreira da Silva, the National Park Director.

After some burning trials, carried out between 1976 and 1981, Moreira da Silva implemented, as the regional head of the Forest Services, an operational prescribed burning program in the north-western region of Portugal. More than adopted, the technique was adapted to the specificities of the region, and was concurrent with research studies focused on its ecological effects. This was the first program of fuel management with prescribed fire in Europe. It began in January 1982 and was extensively applied to maritime pine (*Pinus pinaster*) stands, in the frame of an emergency plan to decrease fire hazard.

The burnings programmed took place in 10 of the forest perimeters of Entre Douro-e-Minho (NW Portugal), which made up 74,280 ha, about 55% of the total area of common lands in the region. The area treated annually has come to exceed 3,000 ha, about five percent of the pine forest under public administration in this region. The implementation was committed to seven teams, consisting of a technical supervisor and a 4-10 hand-crew. The Forest Department of UTAD was requested to follow these experiments and started a R&D program, focused on the environmental and ecological effects of prescribed burning, until 1990. Further studies focused on prescribed fire behavior and technological development, were financed by national and international agencies, namely the European Commission projects FIRE TORCH, FIRE STAR and FIRE PARADOX. The variety of land management goals that prescribed burning can accomplish makes it the most powerful and flexible tool in forest and wildland management. The basic principles guiding the original pine underburning practice in Portugal were extensively disseminated to European foresters since then, including the recent development of a European Prescribed Burning Guide.

To ensure the exchange knowledge and technical skills development in the use of the technique, UTAD partnered with the Portuguese Federation of Forest Producers (FORESTIS) and the Forest Service to carry out knowledge transfer and training courses. Exchange programs with the U.S. Forest Service have allowed training of Portuguese as "burn bosses", hence creating a core of trainers to teach courses in Portugal.

Prescribed fire as a hazard-reduction tool was first mentioned in law in 1981 (DL. No. 55/81 of 18 December). However, only in 2004 was a legal framework for prescribed burning established (DL No. 1061/2004). Since 2004 the PNDFCI (National Plan of Forest Fire Defense) recognizes the importance of prescribed burning in reducing fuels and increasing the territory resilience to wildfire.

A group of fire specialists (GeFoCo) was created in 2006 to coordinate and foster prescribed burning training and operations. Prescribed burning can only be practiced under the responsibility of qualified personnel, according to the technical and functional rules defined by regulation. The Forest Service is in charge of the accreditation. Technicians must be trained to base-level or develop work in fire management, requiring in both cases the frequency with approval of a specialization course. Since 2002 nine technical accreditation actions in prescribed fire have been carried out, with 158 trainees, and 10 operational training courses in prescribed fire have involved 196 trainees.

An approved Prescribed Burning Plan for a maximum of five years needs to be in place before any prescribed burn operation can be carried out. An Operational Burn Plan includes the prescription and other technical specifications, as well as the land owners authorization and other administrative requirements, and a postburn assessment of impact and effectiveness. Prescribed fires are allowed whenever fire danger rating is low to moderate.

6. Characteristics of prescribed burning in Northwestern Portugal pine stands

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In the 1930s most of the communal lands in the mountains northern and central Portugal were widely afforested by the Forest Service, essentially with maritime pine. As a result, the traditional mosaic of grazed shrublands and cultivated fields was replaced over thousands of hectares by continuous, dense and even-aged pine plantations, whose wildfire hazard potential soon became evident. The north-western Iberian Peninsula has the highest fire frequency in Europe, due to the favourable conditions for plant growth. Fuel accumulation in the maritime pine stands of the region is unparalleled by pine forests in temperate climates elsewhere. How to manage this increasing wildfire danger?

Most Mediterranean *Pinus* species have the ability to withstand low- to moderate-intensity fires without damage, making them obvious candidates to prescribed burnings. A prescribed fire aims well-defined effects that will fulfill one or more management goals, which are attained by burning in a specific fire environment (the prescription) and following specific operational procedures (the burn plan). Fire hazard reduction frequently is the main reason to use prescribed burning, but benefits to soil properties and the diversity and nutritive value of understorey vegetation were also expected.

The success of a prescribed fire program depends of adequate planning, which clearly distinguishes prescribed burning from the traditional use of fire. A systematic monitoring and documentation of pre-fire, fire and post-fire variables is a crucial activity to determine whether the pursued objectives have been met. It also is used to assess the operational effectiveness of prescribed fire and provides a sound basis to adjust and refine the practice in the future.

Considerable documentation exists on the prescribed burning operations conducted by the Forest Service in Portugal. The information provided by this data source (493 field forms, from 1979–2001) was retrieved from the Forest Service and translated into a database, to characterize and evaluate management-ignited fires in the pine forest of the Entre Douro e Minho region of northwestern Portugal. This sample, which represents more or less one seventh to one fifth of the total number of burn operations during the study period, is representative of prescribed fire activity in the region.

Slope and elevation in the burned units range from zero to 68% and from 150 to 1000 m, averaging 22% and 520 m. Soils are derived from schist or granite.

The vast majority of the burns were conducted in maritime pine (*P. pinaster*) stands. Distribution of the treated area by cover type is 86.4% (pure *P. pinaster*), 7.9% (dominated by *P. pinaster*), 5.3% (*P. sylvestris*), and 0.4% (*P. radiata*).

The stands subjected to prescribed fire are diverse in structure but carry in general a well-developed understorey layer, composed of evergreen sclerophylous shrubs of the *Calluno-Ulicetea* class. Gorse species (*Ulex europaeus*, *Ulex minor*) - favoured by the oceanic character of the climate and frequently in association with bracken-fern (*Pteridium aquilinum*) - dominate or co-dominate the community in 71% of the stands and account for more than half of total understorey cover in 57% of the cases. Dry sites and inland locations are dominated by the legume *Chamaespartium tridentatum* and by ericaceous species.

Potential heat release is directly proportional to fuel load, i.e. the amount of biomass available to burn, and this variable is therefore a fundamental input to fire behaviour prediction models and systems. Prescribed burning priorities are commonly assigned on the basis of a fuel hazard classification scheme driven by fuel load, whose pre-burn and post-burn estimates allow objective evaluations of the burn success in meeting management goals.

A minor portion (2%) of the prescribed burns is conducted in stands where fine fuel accumulation (averaging 36 t ha^{-1}) and shrub height (2.2 m) are on the opposite end of the fuel spectrum. The task of achieving a balance between proper fuel consumption and acceptable tree damage is complex in this situation, advising the replacement of prescribed fire by a mechanical fuel treatment. It is recommended the application of prescribed fire in maritime pine stands when the fine fuel load exceeds 8–10 t ha^{-1}.

Average understorey height exceeds one meter in 25% of the sites, and the shrub canopy - well aerated, dense, comprised of fine elements with an important dead component - will give rise to tall flames if fully involved in combustion; additionally, flames can be vertically transmitted to the ladder fuels (dead needles suspended in the lower branches of the trees) in unpruned stands.

Fuel-complex structure and the quantity of elevated fuel should therefore be the main causes for the unusual flame dimensions and fire intensity reported for some fires, even when back firing was the method of ignition. The shrub layer dominates the fuel complex and hence has the prevailing role in fire behavior in 75% of the burn units.

The prescribed burning program firstly emphasized pine stands older than 20 years, where fire use was deemed easier by the presence of taller trees and suppressed understorey. Subsequent tree mortality caused by *Scolytidae* insects, especially in dense stands with more than 30 years of age, motivated a shift towards younger age classes, and after 1995 there are no records of fires in stands older than 25 years.

The burning activity takes place in the dormant season, during periods when weather and moisture conditions are conducive to low rates of heat release and selective biomass elimination. The burn season is variable and can extend from November to April, but the frequency and quantity of autumn rain can preclude any burning activity until January. Most fires are conducted from December to February. Prescribed burning is concentrated in January. Forty-one percent of the fires and area burned occurred in this month, when favourable burning conditions coincide with cold dry weather associated with dominance of high pressure systems.

The burn blocks are, in general, delimited by pre-existing barriers, usually forest roads and fuel-breaks, complemented by the establishment of control lines. The fires are started by line ignition (rarely exceeding a length of 200 m) and are conducted as back fires, i.e. against the wind and down slope. When fuel moisture is too high for sustained back fire propagation, head firing (up slope and upwind) is used, ordinarily as a succession of fire lines separated by short distances. The burning crew is composed of a technical supervisor and 4–10 persons that rely solely on hand tools for fire containment.

Prescribed fire in the pine stands of north-western Portugal is clearly a small-scale practice. The average burn lasts for six hours approximately and attains 3.5 ha in size, with mean values by Communal Forest ranging from 0.6 to 7.5 ha. Only 20% of the fires have 5 ha or more (60 ha is the maximum recorded value) and 15% of the burns are smaller than 1 ha. The average burn is accomplished at a rate of 0.52 ha h^{-1}, which is two to five times faster than mechanical and chemical fuel management methods, but mean values by Communal Forest vary in the 0.12–1.03 ha h^{-1} interval.

At the end of the prescribed fire season, mean patch size the average plot that results from adjacent treatment units burnt in different days is 8.6 ha, with a variation by Communal

Forest of 2.0–18.3 ha. Spatial patterns of prescribed burning programs elsewhere are not comparable, since they include burn units larger by one or two orders of magnitude.

Several factors are accountable for the small fire size, including the limited fire suppression capabilities of the burning crews, the heterogeneity and steepness of the terrain, and weather patterns that constrain fire spread rate and fire sustainability (and therefore the number of hours that are available to burn on each day). Fire duration explains 21% of the variation in fire size, with 25% of the fires being ignited after noon but only 10% finishing at 18:00 or later, but other variables were also found to be significantly correlated with the area of a burn.

Burn operations tend to be larger in older stands and stands with less abundant understorey vegetation, which might reflect the use of more conservative ignition patterns where trees are most at risk to suffer damage from fire. An increase in the size of the treated areas is advisable and would be achieved by enlarging the duration of the burns when possible, but especially by increasing the treatment rate through longer ignition lines; in less favourable topographies this would involve additional manpower and fire suppression equipment, i.e. vehicles equipped with water pumps.

Any prescribed fire program is strongly constrained by weather factors. The maritime influence that prevails over the study region attenuates diurnal oscillations in temperature and humidity, making fire behaviour more predictable and facilitating a burn operation. On the other hand, the vegetation growing period is lengthened by such moderating effects and curtails the potential season for prescribed fire. But rainfall poses the major climatic restriction to prescribed burning in the region, ranging annually from 1500 to 2500 mm (among the highest values in Europe) and occurring in more than 40% of the days.

Mean values of air temperature and relative humidity during the burns varied between 9.2 ^{o}C in December to 13.6 ^{o}C in November, and from 63.1% in April to 74.2% in November.

Control problems can arise from an excessively strong wind, while lack of wind, a more common situation, complicates the conduction of the burn and increases tree canopy scorch. Winter dry periods in the study region are often calm, especially when determined by an Iberian high-pressure system. Depending on stand structure and topographical position, wind speed inside a forest is 2–10 times lower than wind speed in the open.

Overall, and because the preferred range of the prescription is rarely observed by the three variables concurrently, only 8% of the fires qualify as optimal. The sub-optimal burns (79% of the total) tend to occur under warmer, calmer, and moister conditions than the 'ideal', a deviation that should increase tree crown scorch and decrease fuel reduction. Since two thirds of the fires were conducted with dead fuel moisture contents in excess of 21%, fuel dampness is undoubtedly the major reason for marginal burning conditions.

The behaviour and effects of a fire are strongly conditioned by fuel moisture, a variable that profoundly affects ease of ignition, combustion velocity, fuel consumption and flame temperature. Such importance is even more noteworthy in understorey prescribed burning, where the ignition pattern is usually designed to cancel the dynamic influences of wind and slope. Moisture content of the fine surface dead fuels was estimated from ambient temperature, relative humidity and time since rainfall, and then corrected for the amount of solar radiation.

Simulated fire intensity in 25% of the plots is low enough (<500 kW m^{-1}) to assure effective fire suppression with minimum resources in a normal summer weather scenario, but the same fuel hazard levels require heavy ground equipment to contain wildfires burning under severe weather conditions.

A fire intensity upper limit in the 250–700 kW m^{-1} range is often recommended for prescribed burning under tree canopies. Estimated fire intensity exceeds 250 kW m^{-1} for 11% of the data base fires, despite the already mentioned conservative prescription for weather.

The hazard-reduction effect of a burn was evaluated in terms of fuel modifications, and by comparing potential wildfire characteristics before and after the treatment. The fuel hazard reduction resulting from a prescribed burn was considered fully effective if the post-treatment fire behaviour level indicated maximum assistance with the suppression of a subsequent wildfire on the site, i.e. the heat release potential of such fire was below 500 kW m^{-1} and was within the control capability of crews equipped with hand-tools.

Prescribed fire in maritime pine stands generally has a strong impact on fine surface fuels, albeit some variation can be expected. The upper litter horizon, with a median consumption value of 100%, is partially removed on occasions only. The corresponding value for understorey vegetation is lower (86%, range of 37–100%), but the most flammable shrub components (foliage and very fine twigs) are usually removed by the fire: post-burn terminal diameter of shrubs' remains is less than 2 mm in only 24% of the burns.

The modified fuel conditions following the application of prescribed fire indicate an average reduction of 96% (with a variation of 59–100%) in the intensity of a wildfire, under extreme summer weather.

Fire severity is the immediate effect of fire on the ecosystem. A general severity rating method can be based on flame length and depth of burn. These variables indicate the upward and downward heat pulses, respectively, and are combined in a two-dimensional classification matrix. This approach was used in the development of a specific method to evaluate the ecological severity of prescribed fire in maritime pine stands.

The potential of flame length (or fire intensity) as a component of a fire severity appraisal scheme is somewhat limited, because the post-fire survival and recovery of trees is linked to their morphology. It seems therefore advisable to replace flame length with a variable related to tissue damage, such as crown scorch ratio (RCs). Damage to needles and buds is the prevalent cause of mortality in *Pinus* species; duff moisture conditions during prescribed burning preclude root injury, and stem injury is unlikely in maritime pine, because the cambium tissue is effectively protected by a relatively thick bark acquired at an early age.

Tree injury is not immediately apparent and requires inspection two to three weeks after the fire. Crown scorch ratio reveals the severity of foliar damage and was calculated as the scorched crown length in proportion of total crown length.

Higher levels of crown scorch are parallel with growth decreases in *Pinus* species, but most studies agree that pines can sustain one or to two thirds of foliage loss without noteworthy detrimental effects on growth. In mature maritime pine stands, prescribed fire does not reduce tree vigor or growth when crown scorch is absent or minimal, but growth loss can be important if more than half of the crown is scorched in length or volume. In maritime pine stands younger than 20 years in northern Portugal, artificially heat injured trees showed significant growth improvements for the lower levels of crown scorch; and similar decreases for the higher levels. Similar results after experimental fires showed negative effects on tree growth for higher RCs and growth increased when the RCs was low.

Forest floor has an important role in soil fertility and stability, and although the desired amount of residual duff can vary by burn objective, the necessity of moderating the organic layer removal and minimise humus consumption. Hence, and given the position of upper duff (between surface fuels and the humus horizon), its consumption (RFc) is used to describe the downward component of fire severity. Similarly to RCs, RFc is expressed as a ratio, positioning the impact of fire in relation to the minimum and maximum modifications that are physically possible. For lower RFc classes the fermentation layer is moderately consumed, but for moderate to high classes can have an excessive reduction of the upper duff and so, some humus is eliminated or even the consumption of the upper duff is nearly total. A considerable amount of the humus layer will be available to burn and the plant structures

below the ground surface can experience lethal heating, depending on their location and duration of the combustion.

Fire severity indicators for the typical prescribed fire indicate minimal impacts on the ecosystem, even if a broad range of variation is possible. Duff removal is slight, and thus the downward heat pulse is expected to be highly correlated with surface fuel consumption, implying minimal smoke production and the absence of negative effects in the soil and root system of the trees.

Pine canopy scorch is restricted to its lower third, and the average tree in a stand will not experience a decrease in growth rate and will survive the immediate effect of the treatment. The upward component of fire severity is therefore more prominent than its downward equivalent, given the generally high fuel accumulation and low tree crown base, the previously mentioned tendency to burn under calmer and warmer weather than the optimum, and because rainless periods are sufficiently brief to prevent deep duff drying.

Seventy-nine percent of the fires are within the boundaries of the acceptable impact region, but this classification can be deemed excessively conservative. The association of the lower classes of crown scorch might as well be considered acceptable (or at least tolerable) and will further increase to 90% of the total the number of prescribed fire operations that are ecologically sound. As expected from previous findings, burns with severe canopy impacts are comparatively more frequent (8.1% of the total) than burns with severe forest floor effects (1.5% of the total only).

The overall impact of a prescribed fire is based on indicators to classify the ecological severity of prescribed fire. RFc and RCs express the immediate and direct impacts of the fire, the so-called first-order fire effects; the second-order fire effects, are indirect outcomes of the fire that interact with other processes, and, on a longer temporal scale, the fire regime.

The frequency component of the fire regime is expected to play an important role in the biodiversity of maritime pine stands. Consecutive burns at interval less than 5 years on a given site are not desirable.

Fires were deemed either severe or non-severe and efficient or inefficient. The severity of 89% of the operations is mild while achieving a fuel-complex modification that provides adequate protection against a wildfire under normal summer weather, but under extreme meteorological conditions such figure is decreased to 59%.

The environmental conditions are important determinants of the practice and achievements of pine underburning. The dominance of sub-optimal - warmer, calmer and moister - than the preferred prescription range act to increase the ecological impact of the treatment (more scorch in the tree canopy) and decrease its effectiveness (less fuel consumption); in addition, the former effect can be exacerbated by fuel accumulation and ladder fuels when fire is used for the first time in a young stand.

Two-stage burning can be recommended to improve the results, and it is sometimes used: a first fire conducted under poor burning conditions is followed by a burn under drier conditions. The occurrence of marginally high levels of moisture content in surface dead fuels is common in the prescribed fire season, due to high relative air humidity and the brevity of rainless periods.

Moisture content is a especially constraining factor, and is a source of difficulty in achieving sustained fire propagation, as well as the main reported reason for cancelling a burn operation.

The selection of treatment units is generally well grounded from the perspective of pre-burn fuel hazard level and, despite the above mentioned environmental limitations, most prescribed fires are successful in achieving the stated objective of hazard reduction without harmful effects to the ecosystem. The structural modifications suffered by the fuel-complex

dramatically reduce the post treatment fire intensity potential, and practically exclude the likelihood of stand-replacement crown fire.

Observations made during wildfires corroborate this, with prescribed burnt areas providing effective assistance to fire suppression. Fuel management is more relevant where the coincidence of extremely dry and windy conditions is unusual, such as in northwestern Portugal, but it is a matter of conjecture whether the current spatial pattern of prescribed fire application, i.e. in relatively small but strategically located strips, contributes to mitigate landscape fire spread in the region. In this paper we have characterized hazard-reduction burning in the pine stands of northern Portugal, and attempted an objective analysis of its results at the operational scale (i.e. the treatment unit).

Finally, from the FIRE PARADOX Web Site the arguments for Prescribed Burning
FOR

Reduces fuel hazard and fire risk
Can benefit the carbon balance by decreasing the overall area burned
Achieves wildlife habitat maintenance/improvement and agricultural goals
Is implemented by highly trained professionals
Applies fire behaviour and fire ecology science to management
It is implemented according to laws and regulations
Supports local and historical uses of fire
Is less expensive than alternative treatments
Increases knowledge of management techniques
Provides training opportunities to fire fighters
Low intensity fires have no detrimental effects on soil

AGAINST

Produces smoke, although always significantly less than uncontrolled fires
Emmits carbon to the atmosphere
Risk of fire escape
Aesthetic impacts
Possible negative effects on plants and animals
Possible adverse effect on soil

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7. The effects of fire on soil properties

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Introduction

Fire is a global herbivore that shaped the global ecosystems for over 350 million years (Bond and Keeley 2005). Fire is also a major earth system process that provides a driving force for the evolution and spread of new plants and biomes (Scott and Glasspool 2006). The post-fire erosion is a factor that also can determine the geomorphological evolution of the landscape (Shakesby and Doerr, 2006).

The earliest scientific literature about the effects of fire on soil properties dates from the 1930s, the same decade Herbert Stoddard and other advocates of fire management were actively encouraging the use of prescribed fire to create healthy, productive environments. After several decades of fire suppression, land managers, scientists, and policy makers began to notice a gradual deterioration of forests and fields. Problematic levels of forest fuels were accumulating in some of the areas where prescribed burning had been discontinued, environmental integrity was declining, and the threat of catastrophic wildfires was increasing. Fire exclusion also led to an abundance of undesirable plant species (http://fire.Forestencyclopedia.net). Several scientific publications appeared in the 1930s in favor of re-introducing prescribed burning, or the use of fire to manage the land. The benefits of 'Indian fires' for longleaf pine forests were reported by Greene (1931) and Chapman (1932) (Stewart 2002). Thus, during the 1930s, prescribed fire was introduced across the southern United States as a forest management technique.

One of the first references on soil effects in literature was provided by Greene (1934). He analyzed the annual burning of grass in a virgin longleaf pine forest and the effects of the fires, particularly on the organic matter content, but also on other soil properties. Heyward (1937) worked on the physical properties of soils in a similar longleaf pine forest and found that excluding fire for as little as 10 years resulted in more porous, penetrable soil. Heyward (1938) also found that single, low-intensity prescribed burns in the southern United States typically did not cause dramatic changes in soil structure and texture. He claimed that the higher soil temperatures during these prescribed fires usually lasted for a short period and, as a result, did not have dramatic consequences.

Walhenberg (1935) also worked on these types of forest, although his results were more focused on the relationship between fire and soil and the reproduction of pines. He also found that infiltration rates were lower in soil from the southern United States that had been burned several times (Walhenberg et al. 1939), a fact also reported by Meginnis (1935) and Arend (1941). Garren (1943) found that soil organic matter content is usually lower in soils that are repeatedly burned, and early researchers noted that burned soils were harder, denser and less permeable than unburned soils.

The **impact of forest fire on soil hydrology** is the key factor of the post-fire ecosystem evolution due to the control the water resources exert on the vegetation recovery and due to the effect of the amount of runoff on the sediment yield. After forest fires, researchers reported an increase in the surface runoff due to a reduction in soil infiltration and water storage capacity (Arend 1941, Anderson 1949). Other studies reported an order of magnitude increase in peak flows and surface runoff after fire as compared to little or no runoff before the fire due to the reduction of the soil infiltration and surface storage (Wright et

al. 1978, Scott and van Wick 1990). During the 1990's and early 2000's research continued to confirm that fire generally reduces infiltration rates and to determine the factors that influence the magnitude of the effect (Robichaud and Waldrop 1994, Martin and Moody 2001). Usually infiltration rates are greater on unburned soil and decrease with increasing burn severity on burned soil (Cerdà 1995). In a wet Mediterranean environment in Portugal, the lowest infiltration rates were found on the recently burned sites and the greatest in the unburned sites (Shakesby et al. 1993); Campbell et al. (1977) also demonstrated that the removal of litter by fire induce more frequent soil freezing, which may reduce infiltration rates. As the vegetation recovers, the infiltration rates return to pre-burn conditions (Cerdà 1998a, 1998b). However, because infiltration rates are dependent on rainfall characteristics, infiltration rates can be greater after a fire than before. Robichaud et al. (2007) found rainfall intensity was the driving factor in post-fire runoff and peak flow responses at six Western U.S. watersheds. Cerdà and Lasanta (2005) found a significant difference in the hydrological response of burned plots due to the rapid vegetation recovery under wet Mediterranean conditions in the Central Spanish Pyrenees.

      Soil burn severity describes the fire-induced changes in the soil properties that impact hydrological and biological soil functions. Some fire effects resulting from the consumption of organic material near and on the soil surface lead to changes in soil properties that change soil infiltration, such as: 1) the formation of or increase in soil water repellency; 2) change in soil structure (e.g., consumption of fine roots increases micro- and macro-pores); and 3) change in bulk density (e.g., due to collapse of aggregates and clogging of voids by ash) (Certini 2005). After prescribed burns in western Montana, Robichaud (2000) compared the effects of soil burn severity on infiltration under simulated rainfall. Infiltration rates of 60 to 80 mm h^{-1} were measured on low soil burn severity plots and decreased as soil burn severity increased. Moderate soil burn severity plots had infiltration rates of 30 to 84 mm h^{-1} the infiltration on high burn severity plots was only had 23 to 55 mm h^{-1} (Fig. 1). Then fire severity is a key factor to control the runoff generation, and this is why prescribed fires can be a useful tool to avoid soil damages due to the wild fires. This effect has been shown by the protective ash layer developed after forest fires (Cerdà and Doerr, 2008). Ash can be a key factor after forest fire as is the unique soil cover for some weeks after the forest fires. Then the changes in infiltration are due to changes in ash properties and depth.

      The **spatial variability of the infiltration rates** observed in many post-fire research studies are often due to the patchy distribution of pre-fire vegetation (Seyfred, 1991; Dunkerly and Brown 1995; Cerdà 1997b; Reid et al. 1999). When a fire burns a patchy (mosaic or tussock) vegetation cover, the bare soil and the soil in the vegetated patch are heated differentially. After the Denio Fire in the rangeland of northwestern Nevada, Pierson et al. (2001, 2006) used simulated rainfall experiments to determine that the coppice microsites (area directly under shrubs) had reduced infiltration rates and increased overland flow due to soil water repellency, while the bare soil between the vegetation was not water repellent and had greater infiltration rates. This is also related to the micro- and macro-pores caused by the vegetation which influences the infiltration capacity of soils. Hubbert et al. (2006) found in chaparral landscapes of California, that fire-induced soil water repellency was preferentially produced under *Ceanothus crassifolius* cover, and this would likely result in variable infiltration rates under natural rainfall. The post-fire recovery of vegetation corresponds to an increase in the heterogeneity of infiltration has been demonstrated in a number of studies (Dunkerly and Brown 1995, Cerdà 1997b, Cerdà and Doerr 2005, Cerdà and Doerr 2007).

      The Post-fire Infiltration Rate Recovery—Temporal Variation. After fire occurs and the soil is covered with ash, the next change in the soil surface is ash redistribution by raindrop splash, surface runoff, and wind. The first rain events easily remove the ash cover, clog the pores with small particles of ash and sediment, and seal the soil surface. These

changes reduce infiltration rates to the lowest post-fire values. However, the same post-fire rainfall events that move ash downslope provide needed moisture for vegetation recovery. As vegetation re-establishes, it protects the soil from raindrop impact and begins to develop the litter layer. These changes due to increased vegetation increase infiltration and reduce surface runoff. The studies in eastern Spain have shown it takes 2-4 years under dry (summer) conditions and 4-6 years in wet (winter) conditions for infiltration to return to pre-fire conditions (Cerdà, 1998a, 1998b). In addition, infiltration rates vary seasonally where there is large variation in seasonal climatic conditions, such as in the Mediterranean (Cerdà 1996). The Pedralba sites were monitored from 1990 (beginning immediately after the August fire) until 1995. Infiltration rates were lowest during the first post-fire autumn rains, after the ash layer was washed downslope. The recovery of vegetation increased the infiltration rates over subsequent post-fire recovery years. The seasonal oscillations of infiltration rates were superimposed on the temporal post-fire recovery of infiltration. The same trends in post-fire infiltration rates over time were observed at the Bolbens en La Costera District study site in eastern Spain following an August 1989 wildfire. Low infiltration rates (45 percent of rainfall) occurred during the first post-fire winter with an increase to 95 percent of rainfall five years later. The infiltration rates during the summer season, when the soils were dry, were greater than in winter with values of 84 to 99 percent of rainfall in the summer of post-fire year five (Cerda et al. 1995).
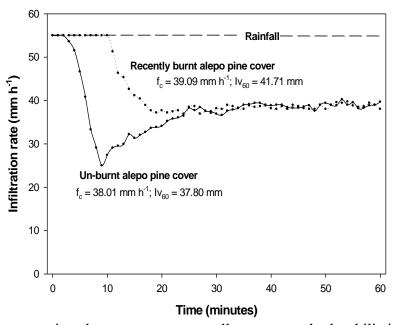

Figure 1. A comparison between a water repellent versus a hydrophilic infiltration curve observed on the Aleppo pine woodland in eastern Spain during summer. The dry and hot soil conditions enhance the water repellent response on the Aleppo pine cover. The hydrophobic response is removed by the effect of fire as shown the fire affected burned soil.
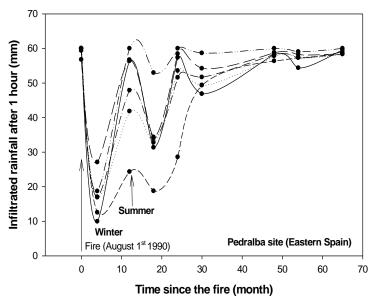
Figure 2. Changes in the mean infiltration rate for Pedralba site, Eastern Spain.
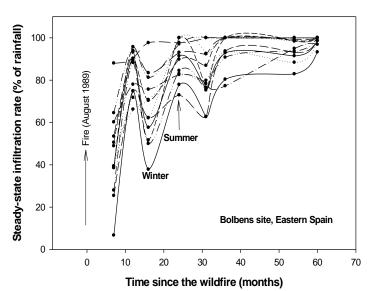

Figure 3. Changes in the mean infiltration rate and variation coefficient for olbens sites, Eastern Spain.

Soil water repellency is not a stable phenomenon. While the soil is wet, hydrologic behavior is normal; however, water repellency often returns as the soil dries (Dekker and Ritsema 2000). Consequently, soil water repellency is generally strongest in the drier summer months. As the hydrophobic substances responsible for water repellency slowly dissolve, soil infiltration and wettability increase. Consequently, as the soil is intermittently exposed to water, fire-induced soil water repellency slowly declines (DeBano 1981, Letey 2001). Although some researchers have measured persistent water repellency from weeks to years (DeBano et al. 1970, Holzhey 1969), fire-induced water repellency is generally broken up after one to two years.

48

Fires and soil temperatures

The transfer of heat to soil is the principal mechanism by which fires affect the physical, chemical, and biological properties of soil (Neary et al. 1999). The effects of fire on the physical and chemical properties of soil depend on the intensity and severity of the fire, and fire intensity is directly proportional to the heat of combustion, amount of fuel consumed, and rate of fire spread. Therefore, fuel types, weather, and topography are important in determining the rate of heat released by a fire. The fuel properties that directly or indirectly affect fire intensity include fuel loading, moisture content, arrangement, chemical composition, and size. Wind speed and other weather conditions that affect fuel moisture also influence fire intensity (http://fire.Forestencyclopedia.net).

The literature contains several definitions of *fire intensity*. For Byram (1959) the *fireline intensity* is the rate of heat energy released per unit time per unit length of fire front, regardless of the depth of the flame zone. According to Chandler (1983) and DeBano et al. (1998), the *reaction intensity* is calculated by estimating the amount of fuel burned per second, and assuming heat yields for the fuel, is usually expressed in kW/m^2. In relation to *fire intensity* and soil properties, Úbeda (1998) defined the fire intensity as the maximum temperature recorded at a certain point and the time that the temperature remains at a certain point, expressed in ºC/s. According to Neary et al. (2005), *fire intensity* describes the rate at which a fire produces thermal energy.

Burn severity describes the response of ecosystems to fire and can be used to describe the effects of fire on the soil (soil burn severity), water system, ecosystem flora and fauna, atmosphere, and society. Burn severity, loosely, is a product of fire intensity and residence time and is generally considered to be light/low, moderate, or high. Given that burn severity is a response to the amount of energy (heat) released by a fire, it usually reflects fire intensity; however, the relationship between fire intensity and burn severity remains largely undefined because of difficulties encountered in relating resource responses to the burning process (Hungerford et al. 1990., Hartford and Frandsen, 1992, Ryan, 2002). Ryan and Noste (1985) and DeBano et al. (1998) developed the following criteria to solve this problem:

- Low burn severity—less than 2 percent of the area is severely burned, less than 15 percent is moderately burned and the remainder of the area is burned at a low severity or unburned.
- Moderate burn severity—less than 10 percent of the area is severely burned, but more than 15 percent is moderately burned and the remainder is burned at low severity or unburned.
- High burn severity—more than 10 percent of the area has spots that are burned at high severity, more than 80 percent is severely or moderately burned and the remainder is burned at a low severity.

According to Jain and Graham (2003), burn severity (sometimes referred to as fire severity) is not a single definition, but rather a concept and its classification is a function of the measured units unique to the system of interest. These systems include flora and fauna, soil microbiology and hydrological processes, atmospheric inputs, fire management, and society; and these system have units of measure relative to the measured responses. For example, in fire management the units of measure include the consumption of organic material, the flame length, the torching index, and other indicators of risk and fire behavior. In terms of the atmosphere, the units of burn severity include particulates and toxic gases as a result of smoke and other inputs from fires. For society, units include the number of homes damaged, injuries and net value changes. Units of measure covering flora and fauna, soil microbiology and hydrological processes would quantify the residual ecosystem structure

after the fire and subsequent responses in terms of nutrient cycling, erosion, species diversity, and recovery rates. The difficulty in the classification of burn severity is to develop consistent and meaningful ecological information that can be easily related to secondary fire effects. Currently, burn severity classifications are either based on qualitative estimates or include detailed information about individual forest components that are difficult to condense into a single classification system. In addition, the measured forest structure may have no ecological relation to the secondary fire effects. The authors critically evaluate the use of burn severity classification in relation to secondary fire effects (erosion, tree mortality, nutrient cycling, and vegetation recovery) and its ecological usefulness and ability to quantify and summarize the information obtained.

The measure of fire intensity is vital to understanding changes in soil properties. Consequently, several authors have studied the changes in soil properties caused by fire (Hungerford et al. 1990, Dimitrakopoulos, et al. 1994, Campbell et al. 1995, DeBano et al. 1998). However, these evaluations are sometimes made in laboratory assessments and can differ widely from prescribed fires and, to a lesser degree, from wildfires. It is difficult to take field measurements of fire intensity and it is generally only possible with prescribed fires. Although real temperature and duration data is essential to understanding the effects of wildfire, the safety risks inherent in obtaining these real-time measurements makes these research efforts very challenging.

Determination of temperatures during prescribed fires

Prescribed fires are used both for research and forest managements purposes. These fires provide the easiest means of recording fire temperatures and durations because the time and location of the fire is known in advance and the site can be instrumented. Some temperature recording methods are only able to register the maximum temperature while others take continuous measurements and can be used to classify fire intensity. It is often valuable to use different methods to compare results (Odion and Davis 2000).

Paints

The use of temperature sensitive paints is an inexpensive method to record temperature maxima within a burned area. A change in paint color indicates the maximum temperature range reached (e.g., between 400 and 500ºC). Several different paints may be used to obtain more refined data. *Evaporation cups*
High heat-resistant porcelain evaporation cups containing the same quantity of water can be placed throughout the fire area. The difference in the volume of water remaining in the cups will indicate the temperatures reached at each location.

Metal

As the melting point differs for various metals, thin metal sticks can be placed throughout the fire. Based on the types of metals that were melted, the maximum temperature range in that area can be determined.

Laser thermometer

Although the laser thermometer was not designed to take field temperature measurements, it can be used in low fire intensity prescribed fires. This type of thermometer can detect differences in surface reflectometry that changes with the temperature. Some laser thermometers have data loggers that record all measurements allowing temperature and

duration to be determined. Although it is possible to take as many measurements as desired, only surface temperatures can be measured.

Thermocouples

Thermocouple thermometers can record the temperature at pre-determined intervals for periods of more than eight hours. These data allow fire intensity to be accurately determined. In addition, thermocouples can be placed on the surface and at different depths within the soil, which allows a temperature and heat duration soil profile to be determined.

Prescribed fires in Catalunya

In Catalunya, what today we know as HIF (High Intensity Fires) started to be known during the 80's. Despite wildfires were always present along the forest Catalan history, they never had such a big magnitude as the wildfire in 1986. 60,000 Ha were burned during that year and a big portion in just one fire, the Montserrat forest fire (Figure 4).
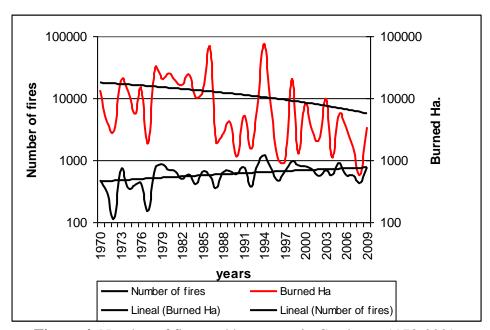

Figure 4. Number of fires and burnt area in Catalunya 1970-2009.

After that year, the territory did not have many wildfires and burned hectares for at least 7 years. Many campaigns addressed to the society from the Spanish and Catalan administrations against the fire remind us that wildfires could be a problem, but almost they were consider a problem from the past.

But, in 1994 Catalunya lived one of the most dramatic episodes; the wildfire which burned more than 70,000 Ha. 1994 was named "the year of wildfires in Central Catalunya". At that time was consider a random episode more than a real problem, but the same phenomenon happened again in 1998 with the "Solsonès fire" and it was very obvious that they were wrong considering previously a random phenomenon. It was clear that there was a management problem with a deep background and it was necessary to find solutions urgently. At that time, just to give an idea, the 0.4% of the forest fires was responsible of the 96% of the total burnt area (GRAF, oral communication).

How can we understand or interpret that the extinguishing services could not fight against the wildfires? In a certain way, the explanation should be searched in the extinguishing service. The efficiency in extinguishing fires reached such a good level that any

fuel which is prone to burn, it will burn. If the extinction is so efficient year by year, the quantity of fuel is increasing exponentially and it is ready to cause a High Intensity Fire. Although now it looks obvious, it was not easy reaching this statement. This is what researchers, managers and stakeholders around the world called: The forest fire paradox. The Paradox says that: "as better we are extinguishing fires, more intense they will be in a risk situation" (Piñol, 2004).

But, in our opinion there are other important factors to explain the problem. Everybody knows that as other places around the world, Catalunya has experienced a rural abandonment during the last decades as a consequence in land uses changes, and this means a forest regeneration where before there was grass or agricultural fields. But not only this, because people who lived in these places they do not use the forest as a source of fuel to be consumed for their activities, so every time the amount of fuel prepared to burnt is bigger (Piqué, 2004).

There is another phenomenon to take into account. A wildfire is the consequence of the "fire triangle": fuel, oxygen and heat, plus a fire ignition point. Many times this start is caused accidentally, intentionally or hazardously. Due to different structural reasons, increasingly urban society get closer to the forests and even houses are built in the middle of the forest just for living purposes, holidays or as a weekends 2nd residence. This phenomenon cause what is named as the rural-urban interface which is in essence a fuzzy and mixed border between these two environments. Additionally, wildfires won't be a problem if we know how to take benefit from the fuel of the forest, but by now, to take a profit from the forest is just an occasional fact.

Managers, stakeholders and authorities once they understood the root of the problem, they thought on solutions. Often, the solutions are not considering good ideas for everybody standards, but what it is sometimes common is that solutions coming from the administration or authorities and even managers or stakeholders are not well considered by the main part of the society (Plana, 2004).

After these HIF's happened, it was time to think on solutions, and not only in extinction, it means, not only, how to fight against wildfires, but to think in the prevention. In 1999 the Generalitat de Catalunya (Catalan Administration) created a group of forest engineers called GRAF (Group of Support to Forest Actions) to be added to the main structure of the fire fighters group of the Administration. This group planned to include fire-fighters in tasks of prevention, and more importantly during all year round in the line of what is a common believe; "wildfires are to be extinted in winter and not in summer". GRAF implement the concept within the fire fighters group of before fight the fire you should know more about the fire's behaviour. The history of wildfires can give us much information on how we have to act against a wildfire, because the behaviour of the fire in many places and situations is always the same. In this way the extinction can be better (Castellnou et al., 2004).

But as we have already mentioned, the GRAF team is working also on prevention. One of the tools that the team implemented to fight against wildfires was the same "fire". Since 1999 the fire is used as a forest manager, a technique named "prescribed fire" or "prescribed burning". The objectives are several, including some of the following; creation of new forest tracks, creation of grass to feed animals, hunting, as well as, the use of the prescribed fire itself as training for the firemen of their logistics and working as a team in a real situation etc. Using the prescribed fire we can avoid the ignition in dangerous places (Galán and Lleonart, 2004).

The objectives to use a prescribed fire are as different and varied as an ecosystem can be and therefore the extinction that should used in every ecosystem. We have to say beforehand that a prescribed fire is not a wildfire. The main difference is that the fire intensity and how this intensity can affect, damage or favour the environment.

52

The prescribed fires are based in the use of low intensity fire conducted artificially in a free way by itself. The prescribed fires are executed following a "prescribed fire plan" prepare before and with the approval of all the staff by means of the "prescribed window", where there are represented the meteorological conditions, topography, quantity of fuel, etc, to obtain a secure prescribed fire and a fire enough intense to achieve the objectives of each prescribed fire (Martínez and Larrañaga, 2004).

Every prescribed fire has a different objective, and depending on this, the prescribed window is different. Once decided this "window" they have an "ignition pattern", it means, a way to start and conduct the fire. Fire patterns can be different but, mainly they are based on the strategies to conduct the fire by means of the head, back or sides of the fire.

Scientifically, the GRAF team has always invited us to be present in all the prescribed fires, and they have been able to use as an experimental plots for research. A prescribed fire is a scenario where we can control many variables necessary to accomplish experiments. And thanks to this we have been researching on the impact of fire on vegetation, fauna, soils, while for technical purposes fire fighters have the chance of necessary training for beginner's fire fighters to understand fire's behaviour before to come across a wildfire. Many research groups take profit of this experimental base.

The prescribed fires are controversial. Many researchers, stakeholders and managers are against prescribed fires as a tool to manage Catalan forests. Therefore GRAF team is interested in motivate environmental researchers to carry out their specific research in every prescribed fire. It is the role of the researcher to study the pros and odds of this kind of management. Catalan forests mainly are not any more natural and they have been managed for centuries. Humans already interfere on the natural forest, and now is the time to keep them alive with their use or sustainable management. In our opinion a big mistake would be leaving these forests as an amusement park after so many years of intense activities and impacts. But, it is necessary to find equilibrium in forest activities between economical feasibility and ecological conservation and restoration.

An example of the effects of prescribed fires in Catalonia:

Recently many researchers have focused their efforts on the effects of prescribed fire on soil chemical properties (Mohamed et al., 2007; Brye, 2006; Grady and Hart, 2006; Garten, 2006; Trammell et al., 2004; Carter and Foster, 2004; Arocena and Opio, 2003; Korb et al., 2004; Gimeno-Garcia et al., 2004; Morley et al., 2003). Not all of these authors dedicated efforts to understand soil nutrient availability. Authors studying the effects of prescribed fire on soil availability inform important differences on the effects. Some of these authors found no significant changes in soil cations after prescribed fire (Trammell et al., 2004), while others observed important changes on soil Ca^{2+}, Mg^{2+} and K^+ (Arocena and Opio, 2003). Also some of them have been studying the effects of experimental fires on spatial patterns of soil properties (Gimeno-Garcia et al., 2004). Soil ecosystem is spatially complex, which requires special methodologies to characterize it accurately over spatial surfaces at different depths. Spatial variability and heterogeneity of soil properties are key to understanding the structure and function of soil biodiversity, soil hydrology and soil productivity. Once the soil heterogeneity is characterized, we can begin to identify soil surface variable processes within a study area. All variables in soil ecosystem show heterogeneity at scales ranging from millimeters to hundreds of meters. Geostatistics were developed to describe the complex patch (3-dimensional) spatial distribution of geologic properties. It is therefore suited to describe the spatial variability and spatial heterogeneity of soil patches, and to provide insight about soil processes and the factors which interact.

Prescribed fires do not burn uniformly across the landscape or even at smaller scales on a hillslope (Robichaud and Miller, 1999). Thus, micro-scale spatial structures may exist for different soil variables such as cations. Moreover, rainfall is an external source of cations (Trudgill, 1988; Feller and Kimmins, 1984) so that the concentration of cations is not conservative. Variability indicates changes, over space or time, in the magnitude of a given soil property. It can be quantified using standard parametric statistics, such as the coefficient of variation, and can be randomly distributed or have a spatial structure. Variability without a spatial structure is called heterogeneity (Ettema and Wardle, 2002) or patchiness and the spatial distributions are not uniform nor random, but aggregated or clumped. By quantifying the structures and scales of heterogeneity, the controls and consequences can be assessed. For soil biotic and abiotic properties, heterogeneity is most often quantified using geostatistics, because of its robust characteristics and mapping possibilities (Ettema and Wardle, 2002). Geostatistics can determine a 2D or 3D model (called a semivariogram or variogram) of the spatial correlations or structures of the soil properties while deterministic interpolation techniques such as inverse distance and triangulation do not take into account the spatial structures of soil properties. Semi-variograms are also important because they provide spatial information that can be used in an interpolation method for estimating values at locations where no data is available.

Soil sampling

The sampling design to know the effects of prescribed fires in the soil is always the same:
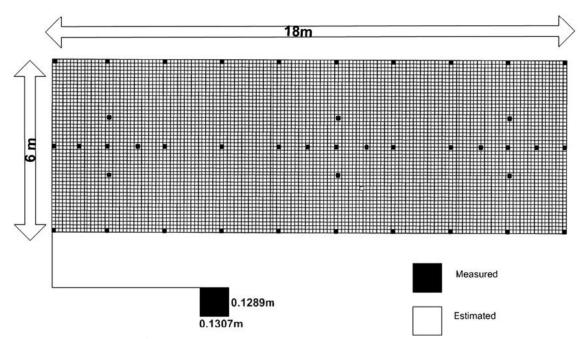
Figure 5. Soil sampling design and size of pixels.

Soil samples (Figure 5) were collected during 6 sampling campaigns from plots and analyzed for Mg^{2+}, K^+ and Ca^{2+}. Samples were collected from the plot: (1) before the PF in May 2002, (2) just after the PF in May 2002, and then (3) two months (July 2002), five months (October 2002), one year (May 2003), and three years (May 2005) after the PF. The plots (6 meters x 18 meters, 108 m2) had 42 sampling points. Three transects consisting of 10 points (spaced 2 m apart) ran from north to south across the plot. These transects were 3 m

apart in the east-west direction. An additional 12 intermediate sampling points were arranged in 3 rhombus patterns along the center transects. Soil samples (5 cm deep from the surface) were collected with a small pick, removed the ashes, air dried in the laboratory, and then sieved to obtain the <2mm fraction. Available Ca^{2+}, Mg^{2+} and K^+ were analyzed using an ammonium acetate extraction (Knudsen et al., 1982) and Atomic Emission Analysis (Whiteside and Milner, 1984).

Summary

We used geostatistics to estimate the evolution of soil cations at fine spatial and temporal scales in a 108 m^2 plot in a complex agricultural landscape after prescribed fire. This geostatistical modeling constitutes a first approach to integrate over time the complexity in soil evolution after the use of fire to manage larger areas. Further improvements should integrate the exhaustive spatial description of vegetation structures.

The index of response measured the percent change in cations relative to pre-fire values. The results suggest that patches on the order of m^2 developed and disappeared during the 3 years of sampling after a prescribed fire. Ca^{2+} was the most sensitive to yield errors in spatial modelisation with the soil sampling design used. Further studies on Ca^{2+} spatial modelisation should look at a finer scale (Figure 6).

The rainfall was a key factor modifying the cation concentrations in the soil after the PF. This PF has provoked distinctive effect regarding the valence of the cations. On the one hand this PF caused on the divalent cations a homogenization effect and on the other hand caused on the monovalent cation a heterogenization effect. The highest rainfall in the spring of 2003 produced two different spatial patterns: (1) the divalent cations Ca^{2+} and Mg^{2+} increased in spatial heterogeneity and decreased the spatial correlation, and (2) the monovalent cation K^+ decreased in spatial heterogeneity and increased in spatial correlation.

In terms of spatial analysis in a plot scale there is a research need of further studies of the effects of fire on soil variables. After the prescribed fire the plot lost progressively potassium and gained magnesium and calcium.
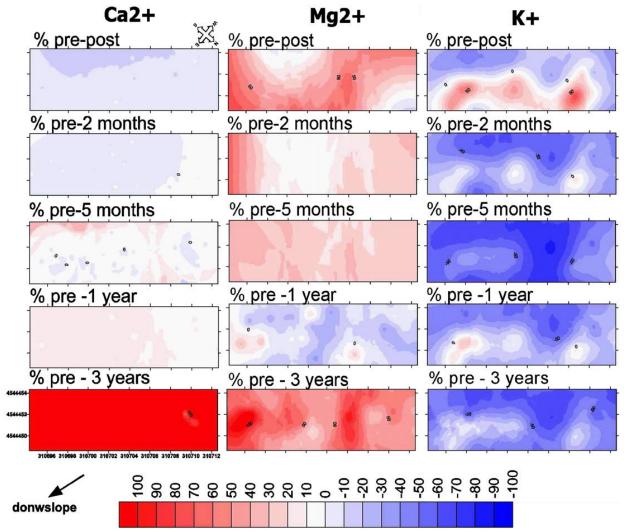
Figure 6. Maps of index of temporal response for the three cations studied.

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