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A novel approach to reduce fire exposure and promote nature conservation in Mediterranean Ecosystems: the case study of Reserva Natural da Serra da Malcata, Portugal

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ABSTRACT

In Portugal, wildfires represent a major concern that yearly produces numerous economic and environmental losses. Currently, there is a continuous increase of biomass accumulation which increases wildfire risk into Mediterranean protected areas due to lack of management. An example is the protected area of Serra da Malcata, where prescribed burning has been implemented. However, fuel treatments implementation within preserved areas remains *quasi* forbidden in the major cases. The main objective is to develop and asses a novel approach to reduce fire exposure and simultaneously promote conservation habitat within Natura 2000 Habitats of Reserva Natural da Serra Malcata. For this aim, fire exposure assessment of three different fuel management scenarios: current situation, planned treatments and low intense treatments within Habitat Natura 2000 promoting conservation goals, were done by using burn probability modelling under extreme conditions for 24h burn period. Results showed similar performance of conservation enhancement scenario if compare with planned treatment scenario. Nevertheless, biggest fire exposure reductions were observed within Natura 2000 network. Limitations and assumptions derived from input parameters, model validation or fire simulator could affect fire exposure results. However, results open the debate to include fuel treatments within protected areas for achieving medium- and long-term fire risk reduction.

Keywords: Fire exposure, Fire simulator, Burn probability, Natura 2000, Portugal.

RESUMO

Novas abordagens para prevenção de fogos florestais e promoção de conservação da natureza no Mediterrâneo: o exemplo da Reserva Natural da Serra da Malcata, Portugal.

Em Portugal, os incêndios florestais produzem numerosas perdas económicas e ambientais anualmente. Atualmente, o aumento contínuo da acumulação de biomassa devido à falta de gestão, resultou no aumento do risco do fogo em áreas protegidas no Mediterrâneo. Contudo, a implementação dos tratamentos de combustível permanecem habitualmente proibidos nas áreas protegidas. O objetivo deste trabalho foi desenvolver e avaliar novas abordagens para reduzir a exposição do fogo e simultaneamente manter os valores de conservação dos habitats da Natura 2000 na Serra da Malcata. Para isso, realizou-se uma avaliação da exposição ao fogo para os seguintes cenários: a atual situação (Cenário 0), tratamentos de gestão de combustíveis de acordo com o plano de gestão (Cenário 1), e gestão de combustível de baixa intensidade aplicada nos tipos de habitat Natura 2000 (Cenário 2). Os resultados mostraram que as diferenças entre os cenários geridos não foram significativas em toda a área protegida. Porém, na área pertencente à Natura 2000, as diferenças foram significativas. Estes resultados permitem abrir o debate sobre a gestão de combustíveis em áreas protegidas visando a redução do risco do fogo a médio e longo prazo.

Palavras-chave: Exposição do fogo, Simuladores do fogo, Probabilidade de arder, Natura 2000, Portugal.

RESUMO ALARGADO

O fogo é um agente modelador da paisagem Mediterrânea, no entanto o regime de fogo tem vindo a alterar-se nos cossistemas Mediterrânicos. Em Portugal, por exemplo, as alterações demográficas e socioeconómicas modificaram o padrão e o comportamento histórico do fogo. Uma maior frequência de incêndios catastróficos nas últimas décadas têm implicado importantes perdas económicas, sociais e ambientais. No caso das áreas protegidas ou classificadas, como por exemplo, parques ou reservas naturais, a não implementação de políticas de gestão da vegetação combustível poderá originar fogos catastróficos e colocar em risco os próprios valores de conservação que se pretendiam proteger com a não intervenção. É por isso importante se a implementação de intervenções de gestão de combustível poderá mitigar a severidade dos fogos e simultaneamente promover objectivos de conservação. Neste trabalho compararam-se diversos cenários de implementação de acções de gestão, usando como estudo de caso a Reserva Natural da Serra da Malcata, uma área protegida situada no centro de Portugal, na qual ocorre um grande número de tipos de habitat da Rede Natura 2000.

O aumento da preocupação com os fogos florestais motivou o incremento de métodos para mapeamenmto e avaliação quantitativa do risco de fogo. Entre estes, o método da simulação de probabilidade de queima tem sido adotado por diversas agências governamentais e gestores do fogo, principalmente em EUA e região Mediterrânea. Muitos dos actuais simuladores de comportamento do fogo incorporam o algoritmo Minimum Travel Time (MTT), o qual permite avaliar tanto o risco do fogo como a eficiência da gestão de combustível, em diferentes escalas espaciais.

A gestão do fogo e do combustível é crucial na tomada de decisão com vista à redução do risco de fogo. A gestão de combustível é, no entanto normalmente restrita e frequentemente proibida em áreas protegidas. No entanto, o risco de incêndio e ocorrência de fogos catastróficos em áreas protegidas pode, em última instância, constituir uma ameaça aos próprios valores de conservação que as áreas protegidas visam preservar. O principal objectivo deste trabalho foi desenvolver e avaliar novas abordagens para reduzir a exposição do fogo em áreas protegidas que simultanemante mantenham ou promovam valores de conservação. Este objectivo foi testado na Reserva Natural da Serra da Malcata (RNSM), em particular nos diferentes tipos de habitat Natura 2000 que ocorrem nesta área protegida. Para se atingir este objectivo, foram analiusados três cenários diferentes de gestão de combustível: nenhum tratamento aplicado, representando o estado actual da RNSM (Cenário 0); tratamentos de gestão de combustível aplicado tal como previsto no plano de gestão (Cenário 1); e gestão de combustível de baixa intensidade aplicada nos

tipos de habitat Natura 2000, visando reduzir o risco de fogos severos e promover metas de conservação a meio e longo prazo (Cenário 2). A avaliação da exposição do fogo e a comparação entre cenários foi realizada através de simulações, usando o RANDIG, (uma versão em linha de comando do software FlamMap), sob condições climáticas extremas e um período de simulação de 24h. As condições climáticas extremas foram definidas usando registos sobre a direcção e velocidade do vento acima do percentil 95, obtidos entre Junho e Setembro.

Os resultados mostraram alterações na importância das classes de fogos de grandes dimensões relativamente ao número total de ignições e de áreas ardidas nos cenários submetidos a gestão, quando comparados com o cenário de referência. A probabilidade de arder e do comprimento da chama condicional média, também diminuiu na área protegida e nos diversos tipos de habitat Natura 2000 para o Cenário 1 e Cenário 2. As diferenças entre o Cenário 1 e Cenário 2 não foram significativas em toda a área protegida. A maior redução na probabilidade de ocorrência de incêndio e comprimento da chama condicional média ocorreu no Cenário 2 e para os distintos tipos de habitat Natura 2000. As classes mais elevadas relativamente à probabilidade de arder e do comprimento da chama condicional média perderam representatividade espacial, do Cenário 2 para ao Cenário 0.

As pequenas reduções da probabilidade de ocorrência de incêndio e comprimento da chama condicional observadas entre os cenários geridos e o cenário de referência podem ser produzidas devido a algumas limitações e pressupostos relativos aos parâmetros de *input*, da validação do modelo e do simulador do fogo. Entre estes pressupostos, os mais significativos estão relacionados com a omissão de informação sobre a supressão do fogo e dos focos secundários, questões de validação do modelo por falta de informação sobre fogos de grandes dimensões e problemas relacionados com a caracterização dos modelos de combustíveis. Para além destes factores, podem também afectar os resultados os pressupostos relativos às condições climáticas e de humidade dos combustíveis serem constantes no simulador e de se ter localizado aleatoriamente os tratamentos de combustível. Os resultados demonstraram que a simulação pode ser usada para informar uma gestão dinâmica do risco do fogo, permitindo abrir o debate sobre a gestão de combustíveis em áreas protegidas visando à redução do risco do fogo a médio e longo prazo.

Palavras-chave: Exposição do fogo, Simuladores do fogo, Probabilidade de arder, Natura 2000, Portugal.

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1. INTRODUCTION

1.1. Wildfire context in Portugal

In Portugal, as in other Mediterranean Basin countries, fire is a natural phenomenon intrinsic to the ecosystems due to environmental conditions characteristics of this area. These environmental conditions are characterized by hot, dry summers and cool winters by rugged relief areas and by natural vegetation typically evergreen, drought resistant and pyrophytic (Nunes et al., 2005).

Wildfires have shaped and are shaped by landscapes. Due to this fire dependency, the majority of the species have evolved in the presence of fire in the Mediterranean Basin (Shlisky et al., 2007) by developing different adaptive mechanisms such as serotinous cones or resprouting strategies (Oliveira and Fernandes, 2009; Pausas et al., 2008). However, many centuries of human activities have changed the recent fire regime altering the “quasi” equilibrium of the landscapes (Pausas and Fernández-Muñoz, 2012). One example of fire regime shift is the decline of the extension occupied by Maritime pine forests in Portugal. Fire return intervals decreased to less than 20 years in some areas which compromised the natural regeneration of the pines (Fernandes and Rigolot, 2007). This generated the decrease of pine extension and also encouraging forest owners to replace pines with eucalyptus, which have rotation periods shorter than 20 years, with consequent increase of the surface covered by eucalypt plantations (Pereira et al., 2006).

Changes in fire regime have altered the Portuguese landscapes. Forest fires are a serious concern in Portugal and in most of the Mediterranean climate countries, where year after year large woodland and shrubland areas burn with severe social, economic and environmental impacts. For example, in Portugal, excluding costs of fire suppression, the social costs of forest fires during the period 2000-2004 were estimated as varying between 200 to 1000€ per hectare of burnt forest, that is, 20 to 80% of the annual forest production (Mateus and Fernandes, 2015).

Statistics from the period 2000 to 2010 show that Portugal had the highest ignition density (24 ignitions per 100 km^2 on average) and the highest mean annual fire incident of the five Southern European countries (Spain, Portugal, Italy, France and Greece), with the 3% of the total forest and shrubland extension burned (Mateus and Fernandes, 2015). Regarding the trend of burnt area in Portugal (Figure 1), there was an increase of the burnt area from 1980 to 2003 followed by a decrease. However the years of 2003 and 2005, registered the major increase of burnt surface area. For example, in the summer of 2003, 440 000 ha burned as a result of the combination of certain conditions in which stood out an extreme synoptic pattern where atmospheric circulation pattern was dominated by a strong ridge located over the Iberian Peninsula (Pereira et al., 2005).

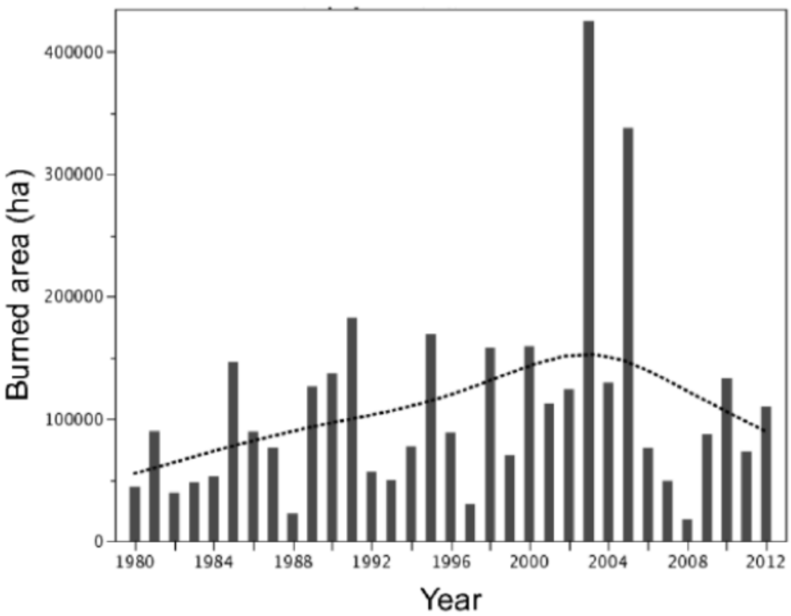

Fig 1. Tendency of burnt area (ha) in Portugal between the period of 1980 to 2010 (Mateus and Fernandes, 2015)**.**

As in many other Mediterranean areas, in Portugal at least 95% of the fires are caused by human ignitions (Rego and Silva, 2014). However the likelihood of fire occurrence varies across Portuguese territory. For example, Catry et al. (2009) used three explanatory factors associated to human presence (population density, distance to road and land use) to forecast probability of ignitions and concluded that human activities were the main trigger of wildfires. In Portugal, the usual pattern of fires in terms of size observed shows that many small size fires are located in densely populated areas whereas fewer, larger fires occur in less densely populated areas (Pereira et al., 2006).

Large fires are not occasional events in Portugal; many have been already recorded in the past. Presently, large fires frequency has increased driven by the interaction of climate, land use change, socioeconomic and policy factors.

Extreme weather conditions account for 10% of the summer days (Pereira et al., 2005) leading to increase both burnt areas and fire sizes (Mateus and Fernandes, 2015). Additionally, according to future climate scenarios, the recurrence of drought and extreme weather conditions will increase in the Iberian Peninsula (Pausas and Fernández-Muñoz, 2012). Beyond weather conditions, socio-economic factors also impact the current situation. Social and economic motivations have produced rural abandonment of many areas rural areas in Portugal. These migrant fluxes towards cities have generated non- or under-managed landscapes (Pinho, 2012) converting the previous agriculture mosaic, grasslands and managed forests into continuous and highly flammable shrublands (Mateus and

Fernandes, 2015) which, in turn, promote fire spread and recurrence (Rego and Silva, 2014). Governmental policies during the last decades have also focused fire suppression rather than prevention, which potentiated inflammable biomass accumulation in the Portuguese landscapes. Policies based on principles “let-it-burn” or managing “unmanaged fires” have been ignored with the consequent fuel vegetation accumulation.

1.2. Wildfire context in Portugal and in their protected areas network

Preserved areas are not exempted of forest fires, which represent a potential conservation risk. In Portugal, the network of protected areas covers 7.6% of the continental area (approximately 680 000 hectares). This network is composed of 1 national park, 13 natural parks, 9 natural reserves, 2 protected landscapes and 7 natural monuments (Departamento de Gestão de Areas Classficadas, 2013). Land cover within protected areas is predominantly composed of shrublands and grasslands (approximately 45% of the area), followed by forests (approximately 23%). Dominant tree species in the network are Maritime pine (*Pinus pinaster*), Evergreen oak (*Quercus ilex*) and Eucalypt (*Eucalytus spp.*) (Departamento de Gestão de Areas Classficadas, 2013). In relation to Natura2000, the pan-European network of classified areas, Portugal has 61 Special Areas of Conservation (SACs) and 40 areas of Special Protection Areas (SPAs). SAC are protected areas defined by the European Union’s Habitats Directive whereas SPAs are protected areas defined by the European Union’s Birds Directive, together conforms the Natura 2000 Network. In Portugal, Natura 2000 network covers approximately 22% of the Portuguese continental territory (2.6 million of hectares) (Instituto da Conservação da Natureza e das Florestas (ICNF), 2015a). The Portuguese networks of protected areas and Natura 2000 overlap geographically in 21 SACs and 18 SPA (Departamento de Gestão de Areas Classficadas, 2013).

Between the years 1995 to 2015, Portuguese classified areas have shown a decreasing trend for the number of fires affecting them and a fluctuation of annual burnt area (between 8 000 and 15 000 hectares). The worst years for burnt classified areas were also 2003 and 2005 (Figure 2).

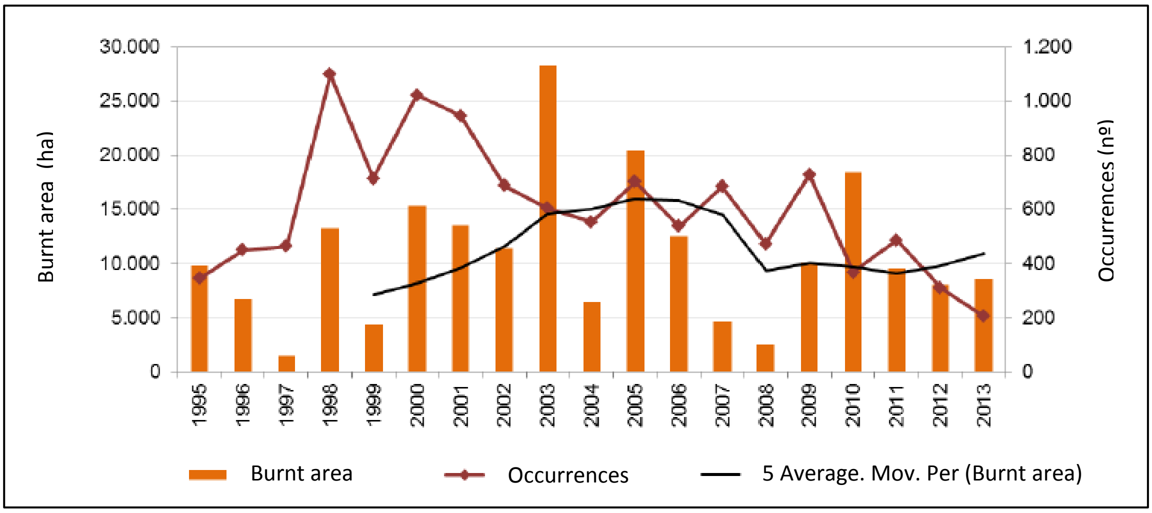

Fig 2. Trend in the number of fire ignitions and burnt area for the period between 1995 and 2013 (Departamento de Gestão de Areas Classficadas, 2013)**.**

Portugal has the worst European statistics for forest fires in terms of burnt area within Natura 2000. Between 2000 and 2010, 364 845 ha of Natura2000 area burnt (approximately 19.1% of Natura 2000 area) (San-Miguel-Ayanz et al., 2012). From 2000 to 2012, an average area of 28 000 ha burnt and covering 74 Natura 2000 sites (Figure 3) (San-Miguel-Ayanz et al., 2012).

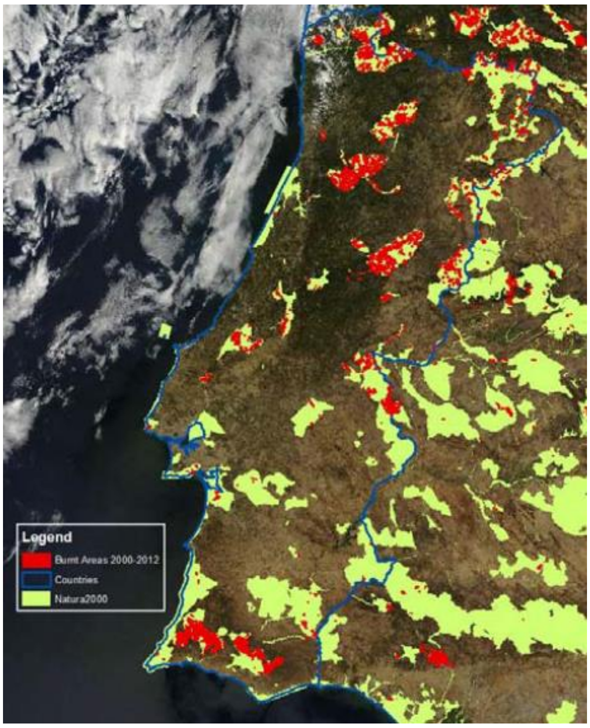

Fig 3. Natura 2000 network of Portugal (green) and the affected areas by wildfires (red) between the years 2000 and 2012 (San-Miguel-Ayanz et al., 2012)**.**

1.3. Fire simulation modelling and its role on fire risk assessment

Wildfires cause loss of economic, social and ecological goods and services every year. As a consequence, there is the need to develop methods that include wildfires events into the decision making processes (Miller and Ager, 2013). Numerous quantitative approaches had been developed for assessing and mapping wildfire risk, exposure and hazard (Finney 2005; Miller & Ager 2013; Salis et al. 2013).

Both fire planning and risk assessment procedures have a vital importance for mitigating wildfires. Such procedures can aid to establish priority areas where locate the wide range of the available fuel treatments (Agee and Skinner, 2005) over different landscape levels, since the other two factors that affect fire behavior, weather and topography, are beyond human control (Finney, 2006a). Besides that, these procedures can be also used for assessing the effectiveness of fuel treatments already applied (Ager et al., 2011, 2007).

However, due to the stochastic nature of wildfires, the quantitative risk-based tools used in risk assessment have to face many sources of uncertainties (Thompson and Calkin, 2011). Several of these uncertainties are related to knowledge limitation for modelling ecological responses. Others are related to the inherent variability of natural systems (Thompson and Calkin, 2011) in which fire behavior and spread vary according to the ignition location, weather conditions, spatial arrangement of fuels and topography (Bar Massada et al., 2009; Salis et al., 2014).

From a risk perspective, the major proportion of burnt areas is generally caused by a very small proportion of wildfires (Ager et al., 2013, 2010; Pereira et al., 2005; Salis et al., 2013). That small proportion of wildfires that escape from the initial attack is due to multiple reasons but is commonly associated with extreme weather conditions and intense fire behavior produced by fuel accumulation that exceeds fire-fighting capabilities (Finney, 2005; Miralles et al., 2010). Therefore, the assessment of the risk produced by large wildfires is necessary. In this context, there has been the tendency to adopt an actuarial approach of the term "risk" for assessing these extreme events. Finney (2005) defined "risk" as the expected net value change of the goods and services on risk at a specific fire behavior (Equation 1). In other words, wildfire risk was defined by interaction of the three components that conform wildfire risk on a particular area and time period: likelihood, intensity and susceptibility (Calkin et al., 2010; Miller and Ager, 2013).

$$E(NVC) = \sum_{i=j}^{N} \sum_{j=1}^{n} p(F_i) \left[RF_{ij}\right] \qquad \text{Eq.1}$$

where $p(F_i)$ is the probability of a fire at intensity i and RF_{ij} is the response function (RF) which measures the net change to value j from the fire intensity i . Thus, the risk is the product of the wildfire exposure, composed by likelihood and intensity, with the susceptibility represented by the former and latter, respectively (Salis et al., 2014).

This approach has advantages over other methods to assess wildfires risk, which integrate all wildfire elements within risk ratings or discrete indices (Miller and Ager, 2013). For example, Chuvieco et al. (2010) developed a wildfire framework that integrated fire behavior aspects together with different socio-economic and ecological aspect and values by using different discrete indices for this aspects .

The actuarial approach of "risk" has been used for estimating wildfire risk of socio-economic and ecological values not only at small scales within protected areas (Ager et al., 2007) or within the wildland urban interface (WUI) (Ager et al., 2006) but also at broader scales (Calkin et al., 2010; Thompson et al., 2011). However, this method also presents some issues when response functions are needed to estimate all the values at risk. This is the case of the effects over non-market values, which are difficult to estimate (Finney, 2005) because monetarize the effects of wildfires, both positive and negative, over ecological and social values continue to be difficult to predict (Venn and Calkin, 2009). Besides the issues related to the response function estimation, risk assessment is more complex and difficult to communicate than others such as exposure analysis (Ager et al., 2014a).

For that reason, fire exposure analysis appears as a simpler and easier method to analyse wildfire behavior. Exposure analysis is a necessary step in wildfire risk assessment and describes the spatial juxtaposition of values with fire behavior in terms of likelihood and intensity but it does not detail the effects of wildfire over the good and services (Finney 2005; Fairbrother & Turnley 2005). Fire exposure analysis has been widely used both in Western United States and in the Mediterranean basin for planning fuel treatments allocation or assessing their performance (Salis et al., 2014).

Fire exposure assessment can be done following two different approaches. On one hand, the deterministic models employ different approaches that usually fall under the umbrella of the artificial intelligence, expert systems with knowledge bases, fuzzy logic and/or neural networks (Thompson and Calkin, 2011). On the other hand, the probabilistic methods comprise different approaches for estimating wildfire exposure. The most important are the logistic regression models (e.g., Catry et al. 2009; Gonzalez et al. 2006; Martínez et al. 2009; Ager et al. 2014) and simulation modelling (e.g. Ager et al. 2013; Bar Massada et al. 2009; Ager et al. 2014; Finney et al. 2011; Salis et al. 2013).

Fire exposure analysis based on probabilistic methods can represent fire likelihood as ignition probability or as burn probability. Generally, ignition probability is built with estimated ignition data whereas burn probability, defined by the probability that a fire encounters a particular place, is estimated mainly by fire simulations (Miller and Ager, 2013). Both methods are widely used, although ignition probability approach is typically applied for initial attack simulations while burn probability is often used for fuel management (Miller and Ager, 2013).

Since some years ago, simulation modelling has been commonly used for analyzing fire exposure, fire risk and mitigation strategies, at different scales that go from stands of few hectares to landscapes (<10^5 ha), regional (<10^7 ha) or national scales (Calkin et al., 2011). Many fire behavior simulators have been developed for these purpose such as FARSITE (Finney, 2004), BehavePlus (Andrews, 2009), FVV-FFE (Rebain, 2010), FlamMap (Finney, 2006b) or RANDIG (Finney, 2006b). Even, sometimes they are integrated in the same simulation process and used together with ArcFuels (Vaillant et al., 2013), a geospatial interface that aids simulation modelling for assessing results of different fuel treatments (Ager et al., 2011, 2010). Furthermore, if the data and computing capacity are enough, simulation modelling is one of the best option to approach exposure analysis, since captures both stochasticity and fuel contagion (Thompson and Calkin, 2011) what, in turn, improves the assessment of fuel treatment performance (Ager et al., 2006).

Development and advances in fire spread algorithms such as the Minimum Travel Time (MTT) (Finney, 2002) joined with the increase of the computational capacity reinforced the use of wildfire behavior modelling . In fact, these algorithms are integrated mostly in all the above mentioned fire behavior simulators. Currently, fire simulators such as RANDIG or FlamMap are able to saturate landscapes with thousands of ignition in order to estimate burn probability at different fire intensities (Ager et al., 2007; Salis et al., 2013), what facilitate and support policy decision-making processes related to the risk assessment of environmental and human values. Much work has been done both in USA and Mediterranean Basin region by using this approach. Bar Massada et al. (2009) conducted a work where it was assessed fire exposure over ecological values and human structures within the WUI, where different fuel treatments had been done by using simulation modelling. Other works have measured exposure over ecological values in protected areas in order to aid the prioritization of fuel treatment allocation or the optimization of fuel treatment already allocated in a local scale (Ager et al., 2007), landscape scale (Ager et al., 2012; Kalabokidis et al., 2014, 2013) or at regional scale (Ager et al., 2014a, 2013; Salis et al., 2013).

2. OBJECTIVES

Wildfires are one of the major threats to Portuguese forests and woodlands and these threats may even increase in protected areas. For that reason, wildfire management is an important process that must be conducted in protected areas and elsewhere. In this context, fire exposure analysis by simulation modelling seems to be an excellent tool for detecting the most vulnerable areas that should be treated or to assess the performance of future planned fuel treatments within preserved areas.

The application of fuel treatments within preserved areas is usually subjected to a strict governmental regulation which many times are forbidden due to conservations concerns. However, due to the conditions above mentioned, the non- or sub-management of fuels in classified areas may generate catastrophic wildfire effects.

The main objective of the present work is to develop and assess a novel approaches to reduce fire exposure and simultaneously promote the protection and conservation within classified areas using the protected area of Reserva Natural da Serra Malcata (RNSM) in Portugal, as an example.

More specifically:

- Three different scenarios of fuel management treatment under extreme climatic conditions were simulated: Scenario 0 - no fuel treatment applied, which represents current status in RNSM, Scenario 1 - planned fuel treatments from the different fire management plans are applied and Scenario 2 - low intensity fuel treatments are applied in Natura 2000 habitat types within RNSM aiming to reduce risk of fire risk and to promote conservation goals for medium- to long-term.

- Risk exposure assessment of RNSM and the Natura2000 habitat types (total area and types of habitat affected) within RNSM is calculated by simulation modelling for the 3 different scenarios and weather conditions.

3. STUDY AREA

3.1. Study Area: Reserva Natural da Serra da Malcata

The Serra of Malcata (RNSM), is protected area occupying 16 158 ha located in central Portugal between the municipalities of Penamacor and Sabugal, which belong to Castelo Branco and Guarda districts (Figure 4).

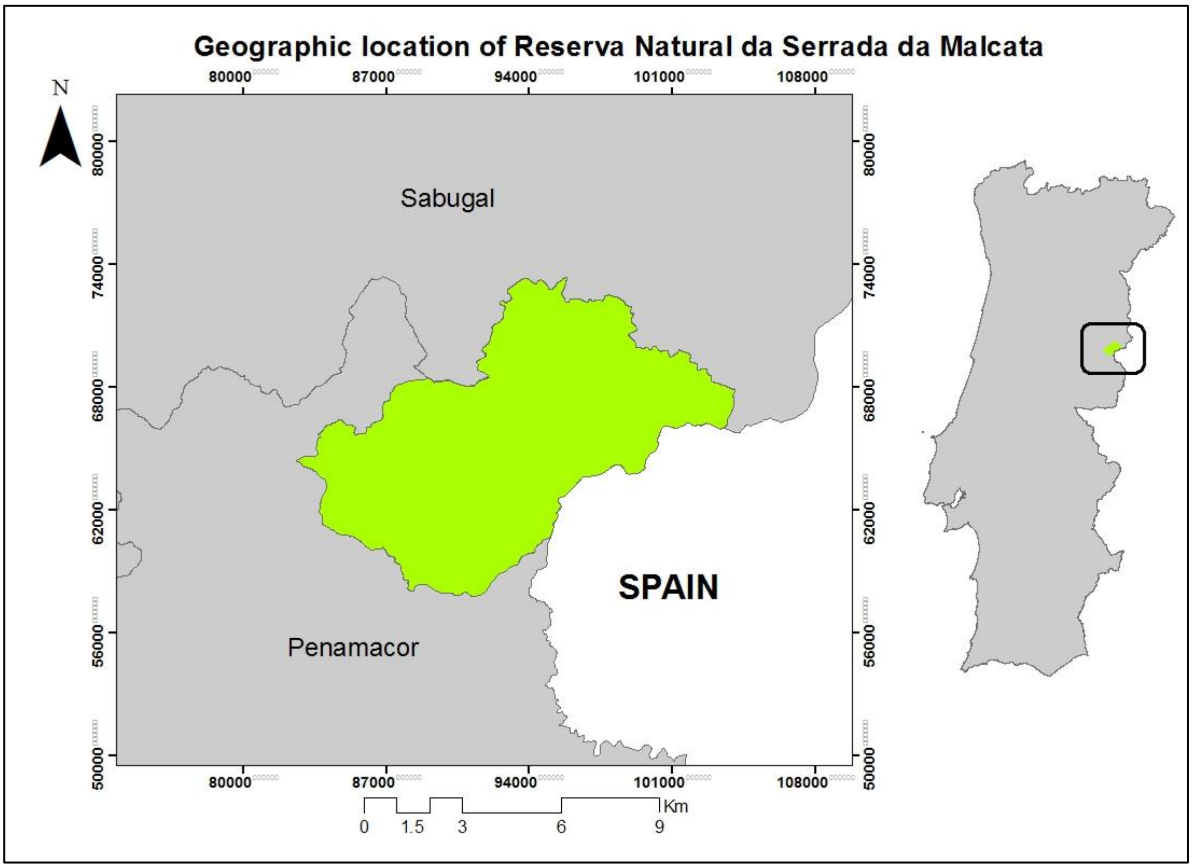

Fig 4. Geographic localization of Reserva Natural da Serra da Malcata (in green) within Portugal.

There is no human population living in the core of RNSM with exception of some disperse houses located along the Meimoa and Bazágueda rivers. The closest population centers are the parish of Penamacor, Meimoa, Meimão, Malcata, Quadrazais, Vale de Espinho and Fóios.

3.1.1. Physical and biological context of Reserva Natural da Serra da Malcata

3.1.1.1. Physical context

RNSM is settled down over bedrock composed in its majority by slate and greywacke. There are two quartz veins that go through the area that originate the crests of Serra da Malcata. In addition, along the watercourses are founded alluvium deposits constituted by quartz, quartzite, hornfels, slate and grauvacks. From a lithologic point of view, the composition is little varied (Instituto da Conservação da Natureza e das Florestas (ICNF), 2003). Regarding the pedology, the area with a slate origin has a majority of low developed soils because of the complex relief and centuries of human activities (Teixeira et al., 1965). There is a latitudinal gradient of soil evolution from the not evolved soils of the south towards the more developed soils of the north. However, there are patches of developed soils inserted between the low evolved soils (Instituto da Conservação da Natureza e das Florestas (ICNF), 2003).

RNSM is characterized by a Mediterranean climate with a marked seasonal variability and a dry period inducing plant water stress during the summer season. Mean annual temperature varies between 10.5 and 15.7 ºC and mean annual precipitations between 849 and 1195 mm/year (Instituto da Conservação da Natureza e das Florestas (ICNF), 2003). Predominant winds coming from west, south and northwest are the most common along the whole year.

RNSM has an average altitude of 800m that decrease from NE towards SW. Maximum and minimum altitudes reach 1078 m and 425 m, respectively. The main ridge which separates the Duoro and Tejo watersheds, divides the preserved area in two different topographic zones. At the meridional part, altitude variations are more marked between the 425 m and 1078 m with predominant south and west aspects. At the septentrional zone, mean altitude is higher, varying between 800 m and 1000 m and with a relief less abrupt. The hydrographic network, deeply inserted in slates, is mainly formed by the sub-watershed of Bazágueda River, the Meimoa floodplain and Côa River. Bazágueda River goes along the main ridge that separates Duoro and Tejo rivers from north towards south and southwest. Meimoa floodplain, affluent of Zêzere River, goes through the preserved area from east to west with abrupt slopes. Côa River marks the north border of the preserved area goes towards the north seeking the Douro River (Instituto da Conservação da Natureza e das Florestas (ICNF), 2003).

3.1.1.2. Flora and fauna context

The vegetation of the Reserva Natural of Serra Malcata is conditioned by the diverse physical factors of the area together with centuries of human activities. Shrubland is the dominant land cover, occupying the 62% of Malcata, whilst autochthonous forests and pine and eucalyptus forest plantations of cover 9% and 18% of the area, respectively. Agro-forestry and croplands, pastures and human infrastructures are almost marginal within the protected area with 2%, 2% and <1% of RNSM respectively (Table 1). There are 5 National endemic flora species, 51 Iberian endemic species and other protected species (classified in Annexes I and II of the European Habitat directive (European Commision, 1992) occurring in RNSM.

The flora of RNSM can be divided in five big landscape units (Instituto da Conservação da Natureza e das Florestas (ICNF), 2003):

Autochthonous vegetation and forests: Human activities such as agriculture, livestock and forest plantations done few decades ago have limited indigenous vegetation and forest to watercourses or more remote areas. The most representative autochthonous vegetation and forest are characterized by Holm oak (*Quercus rotundifolia*) forest, by mixed forest of Pyrenean oak (*Quercus pyrenaica*), Holm oak (*Quercus rotundifolia*) and Strawberry tree (*Arbutus unedo*), by Pyrenean oak (*Quercus pyrenaica*), by Strawberry tree (*Arbutus unedo*) and by riparian forest.

Shrub communities: There are different dominant shrub associations or species. The most dominant species are Gum rockrose (*Cistus ladanifer*), Heath (*Erica spp.*), Heath-Carquesia (*Erica spp.- Chamaespartium tridentatum*) and Brooms (*Cytisus spp.*). The dominance of the different species varies according a latitudinal and aspect range. At the north part of the main ridge that divided RNSM, *Cytisus* species are the dominant shrub communities. Meanwhile in the south part, the dominance of Gum rockrose is limited to south aspects where harsh conditions are founded. Heath and Heath-Carquesia associations are dominant in north aspects.

Agroforestry, croplands and pastures: Despite of the abandonment during the last decades, there are still small areas close to forest plantations and along the floodplains. Within type of land cover, there are annual crops, pasture lands, olive groves and Chestnut and Cork oak *montados*.

Forest plantations: The strong rural abandonment and the consequent land abandonment produced land use changes from cropland to forest stands for production. The majority of the forest plantations are ownwd by Portucel-Soporcel group (gPS) company and ICNF, communal lands and private owners. The most used tree species were Douglas-fir (*Pseudotsuga menziezii*), Maritime pine (*Pinus pinaster*), Black pine (*Pinus nigra*), Eucalyptus *spp.* It is found also areas planted with Douglas-fir and Chestnut that currently have been colonized by Pyrenean oaks. Besides them, it exists small areas of Stone pine (*Pinus pinea*), Scott pine (*Pinus sylvestris*) and Radiata pine (*Pinus radiata*).

Human structures: RNSM contains some water reservoir areas corresponding to the Côa and Meimoa floodplain located in the western border. There are some small constructions within the preserved area too.

Regarding vertebrate species, 208 terrestrial vertebrates and 9 freshwater fish species were recorded in RNSM. Within these 3 species of freshwater fishes, 7 species of amphibious, 3 species of mammals are classified under Annex II of the EU Habitats Directive and 2 species of birds under the EU Birds Directive.

A main reason for the classification of RNSM was the presence of the Iberian lynx (*Lynx pardinus*), a critically endangered feline. Although extinguished in this area, RNSM is considered an emblematic area of Portugal where Iberian lynx last occurred. Other endangered mammal species within RNSM are the Iberian wolf (*Canis lupus*) and the wildcat (*Felis silvestris*) (Instituto da Conservação da Natureza e das Florestas (ICNF), 2003).

3.1.2. Socioeconomic and ownership context of Reserva Natural da Serra da Malcata

3.1.2.1. Socioeconomic context

RNSM, localized in the interior of Portugal, follows the general socio-economic and demographic trends characteristic of the interior and rural areas of Portugal. The municipalities, where RNSM is included, are facing a continued decrease of population density, population aging and an inversion of the population pyramid.

The predominant economic activities of the area are linked to the primary sector. Subsistence agriculture is still common mainly close to the river floodplain. It is also possible to find small olive groves, chestnut *montados* and grasslands used for livestock production in the western and northern zones of the area.

Forestry is a main economic activity of the area. During the last decades, large areas of RNSM were planted for timber production. Afforestation was mainly conducted by private owners using European Union funds.

3.1.2.2. Ownership regime

In RNSM, the state owns an area of approximately 6100 ha. This area is managed under public or private regime according to the given use. Public regime is applied in areas managed by ICNF (mainly center and south of RNSM) whereas private regime, the area in which the state works as a company, occurs in the Mata Nacional da Quinta da Nogueira an area located in the southeast of the preserved area.

Communal lands occur in the parishes of Malcata, Quadrazais and Fôios occupying approximately 928 ha in the north part of RNSM. The company Grupo Portucel-Soporcel (gPS) owns approximately 2500 ha under forestry regime. Finally, 7940 ha are under other private ownership for timber production purposes.

3.2. Protection status of Reserva Natural da Serra da Malcata

RNSM is classified as a Natural Reserve within the Portuguese network of Protected Areas network, and internationally recognized under other environmental classification schemes such as:

- Corine biotopes project. RNSM is part of this project since 1986 with the number CI2800014. The main purpose of this project is to create an information system which collects the state of the environment and natural resources.
- European network of biogenetic reserves. RNSM was declared as part of this network in the year of 1986. The aim of this network is to guarantee the biological, conservational balance and to potentiate the genetic variability and representativeness of the habitat types and ecosystems.
- Bona Convention (1979) which is related to Migratory Species and Berna Convention related to Conservation of European Wildlife and Natural Habitats (1979) conservationist objectives.
- Council Directive 2009/147/EC on the conservation of wild birds (Birds Directive). RNSM was declared as Spatial Protection Area (SPA) in 1999 with the code PTZPE0007. Within RNSM, there are 23 bird species classified in Annex AI, 15 in the Annex AII and 1 in the Annex AIII. Council Directive 92/43/EEC on the Conservation of natural habitats and of wild fauna and flora (Habitats Directive) which classified RNSM as a Special Area of Conservation (SAC) in the year of 1999 and registered with the code PTCON0004. Within RNSM, there are 9 habitat types classified under Annex BI, 8 flora species belonging to the Annex BII and 18 species in the Annex BIV. SAC covers 79 000 ha, that is all area of RNSM. Natura 2000 network, a pan-European network of nature protection areas.

3.2.1. Natura 2000 Habitats within Reserva Natural da Serra Malcata

There are 11 habitats included in the Annex B-1 of the Directive Habitats within RNSM (Instituto da Conservação da Natureza e das Florestas (ICNF) (2003), Grupo Portucel Soporcel (2012)covering 7462 ha or 46% of the area of RNSM. These habitat types are:

- Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (*Alno-Padion, Alnion incanae, Salicion albae*) (91E0): Riparian forests of *Fraxinus excelsior* and *Alnus glutinosa* associated with arborescent galleries of tall *Salix alba*, *S. fragilis* and *Populus nigra*, along hill or sub-montane rivers.

- Natural eutrophic lakes with *Magnopotamion* or *Hydrocharition* - type vegetation (3150): Lakes and ponds with mostly dirty grey to blue-green, more or less turbid, waters, particularly rich in dissolved bases (pH usually > 7), with free-floating surface communities of the *Hydrocharition spp* or, in deep, open waters, with associations of large pondweeds (*Magnopotamion spp*).
- Water courses of plain to montane levels with the *Ranunculion fluitantis* and *Callitricho-Batrachion* vegetation (3260): Water courses of plain to montane levels, with submerged or floating vegetation of the *Ranunculion fluitantis* and *Callitricho-Batrachion* (low water level during summer) or aquatic mosses.
- European dry heaths (4030): Ibero-Atlantic Erica-Ulex-Cistus heaths. Total occupied area is 4632 ha and it is the largest habitat Natura 2000 within RNSM.
- Thermo-Mediterranean and pre-desert scrub (5330): Scrub formations characteristic of the thermo-Mediterranean zone. The extension occupied is 124.3 ha.
- *Calaminarian* grasslands of the *Violetalia calaminariae* (6130): Generally open natural or semi-natural grasslands characterized by a highly specialized flora, with subspecies and ecotypes adapted to heavy metals. They are associated to *montados* areas within RNSM. The extension occupied is 2.6 ha.
- Lowland hay meadows (*Alopecurus pratensis, Sanguisorba officinalis*) (6510): Species-rich hay meadows on lightly to moderately fertilized soils of the plain to submontane levels. The extension occupied is 97.6 ha.
- Siliceous rock with pioneer vegetation of the *Sedo-Scleranthion* or of the *Sedo albi-Veronicion dillenii* (8230): Pioneer communities of the *Sedo-Scleranthion* or *the Sedo albi-Veronicion dillenii* alliances, colonizing superficial soils of siliceous rock surfaces. The extension occupied is 3.2 ha.
- Galicio-Portuguese oak woods with *Quercus robur* and *Quercus pyrenaica* (9230 pt2.): *Q. pyrenaica* -dominated forests. The extension occupied is 784.3 ha.
- *Castanea sativa* woods (9260): Supra-Mediterranean and sub-Mediterranean *Castanea sativa*-dominated forests and old established plantations with semi-natural undergrowth. The extension occupied is 19.2 ha.
- *Quercus ilex* and *Quercus rotundifolia* forests (9340): Forests dominated by *Q. ilex* or *Q. rotundifolia*, often, but not necessarily, calcicolous. This Occupies 1668.8 ha.

Some of them are grouped together because appear associated. For example, protected habitats 3150, 3260, 5330 and 91E0 with 2.17 ha are found within RNSM associated in some area. Other association is 8230-9340 which occupied a surface of 127.8 ha (Figure 5).

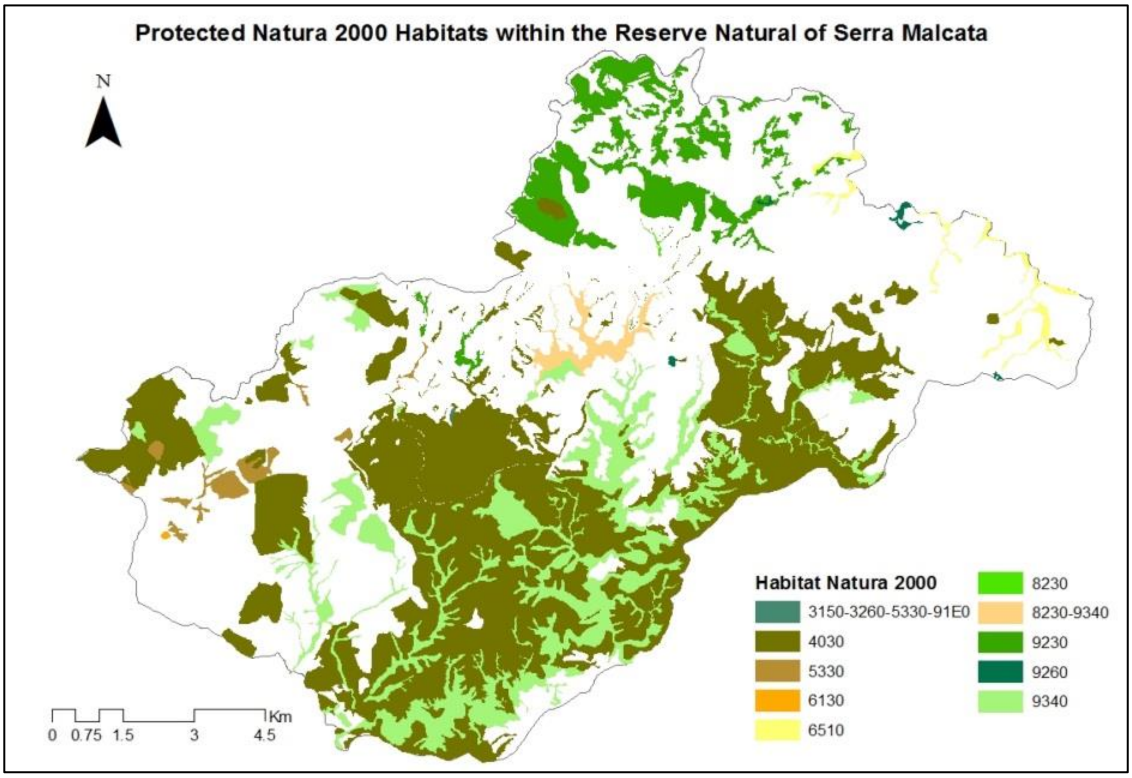

Fig 5. Natura 2000 habitats catalogued within the Reserva Natural of Serra da Malcata.

3.3. Fire incidence characterization of Reserva Natural da Serra da Malcata

Fire statistics of the RNSM between 1990 to 2014 years shows a decrease tendency in both burnt area and number of fire occurrences (Figure 6).

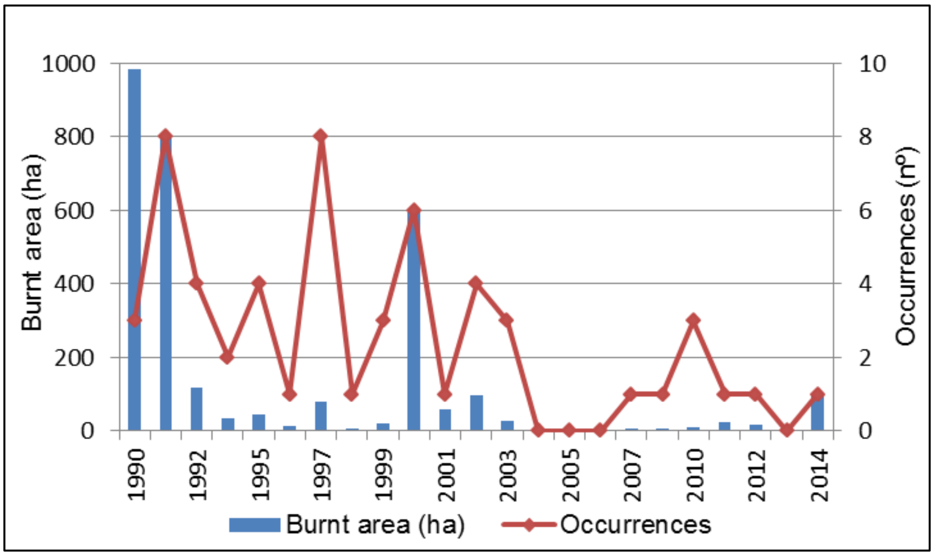

Fig 6. Trend in the number of fire ignitions and burnt area for the period between 1990 and 2014 within the Reserva Natural da Serra da Malcata.

In general, the mean annual burnt area in RNSM has been low for the last 26 years since the area affected by fires has been on average 50 ha (<1% of the total preserved area) mixed with years of fire absence. However, there is the exception of three years (1990, 1991 and 2000) in which the affected area was over 500 ha until 1000 ha (Figure 6). Regarding to the number of fire occurrences, the trend shows the decrease of ignitions within RNSM in the last 26 years. It results interesting the absence of ignitions between 2004 and 2014 (Figure 6). One of the main reasons that have produced this tendency, besides to the improvement of the fire suppression strategies, is explained by the fuel treatment actions accomplished by gPS since this company acquired their properties at the beginning of the 90s'.

Forest fires within RNSM are mainly spatial located in the north, north-east and south-west of the preserved area, very close to Vale do Espinho, Foios, Quadrazais, Malcata and Meimoa villages (Figure 7). The majority of the forest fires, which are located in the north area of RNSM, were originated within communal lands, areas in which are developed agriculture and livestock activities.

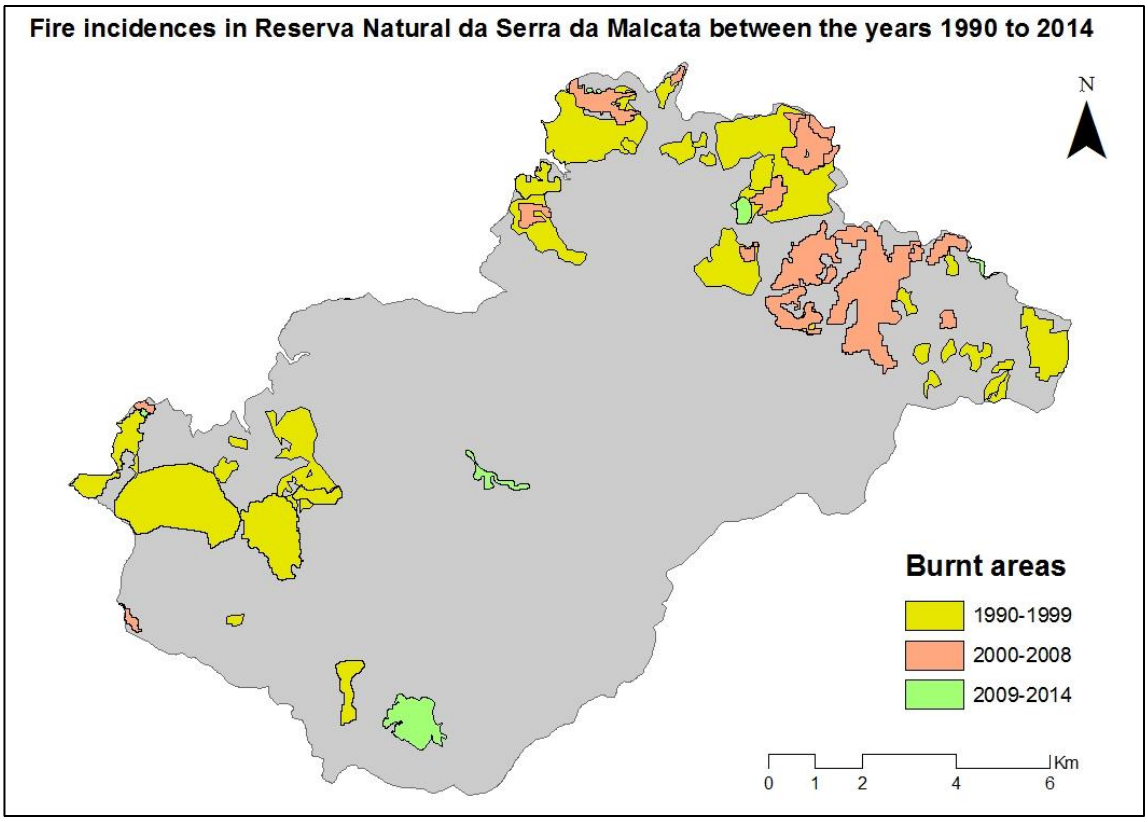

Fig 7. Spatial location of burnt area within RNSM for 1990-1999, 2000-2008 and 2009-2014 periods

4. FIRE SIMULATION

4.1. Fire simulator: RANDIG

The simulation method adopted for simulating the three scenarios was based on previous research studies (Ager et al., 2012, 2010, 2007; Kalabokidis et al., 2013; Salis et al., 2013) although some adaptations were done for being applied to the study area. Wildfires were simulated using the minimum travel time (MTT) fire spread algorithm of Finney (2002) by its implementation in a command line version of FlamMap named RANDIG (Finney, 2006b).

MTT algorithm uses Huygens' principle for replicating fire growth. Fire propagation is generated by wave fronts which usually have ellipsoidal shapes (Finney, 2002). MTT calculates fire growth by finding the paths with the minimum travel time among the nodes of the grid (Finney, 2006b). An advantage of MTT over other fire growth methods is that produces less distortion of the generated fire shapes and have a better response to temporally varying conditions than techniques in which model fire growth from cell-to-cell on a gridded landscape (Finney, 2002). In RANDIG, the MTT algorithm is parallelized for multi-threaded processing (computations for a given fire are performed on multiple processors) making possible to generate thousands of ignitions (> 100,000) which in turn makes feasible to generate burn probability surfaces for large extensions (10,000 to 2 million ha) (Ager and Finney, 2009). This fact reduces the computational requirements for doing simulations and decreases considerately the processing time if compare with other fire growth models such as the one used in FARSITE fire simulator (Finney, 2002). Many tests had shown that MTT algorithm replicates accurately large fire boundaries on heterogeneous landscapes (Ager and Finney, 2009) and for that reason, its use is widely applied in U.S. for wildfire management and issues (Salis et al., 2014).

In RANDIG as in many other fire simulators, fire spread is predicted by Rothermel's surface spread models equations (Rothermel, 1972) and crown fire rates of spread is forecasted according to Van Wagner (1977) as implemented by Scott & Reinhardt (2001). In addition, RANDIG assigns by default a spotting factor of 10%. In contrast to FARSITE, FlamMap and RANDIG assume constant wind direction, speed and fuel moisture what convert both of them in useful tools for simulating short range assessment of fire growth in single fire ignition events (Ager et al., 2011).

RANDIG outputs are: burn probability (BP) and the frequency distribution of flame lengths in 20 classes according to intervals of 0.5 m (0-10 m) for each pixel. In addition, it also creates a shapefile with the burn perimeters and a text file with the burned areas (ha) generated by the simulated wildfires.

As previously referred, burn probability is a measurement of fire likelihood which is widely used for doing comparative risk and exposure analysis (Ager et al., 2011; Miller and Ager, 2013). BP represents for each pixel the chance to burn given a single random ignition within the study area and according to the assumed weather scenario. This measurement was defined as:

$$BP = {}^{F}/_{n} \qquad \text{Eq. 2}$$

where F is the number of times the pixel was burned and *n* the total number of fire ignitions simulated. Fireline intensity (FL, kW/m), which was defined by Byram (1959), is forecasted by the MTT fire spread algorithm depending on the direction the fire encounters a pixel relative to the major fire spread direction *i.e.* heading, flanking or backing fire; as well as slope and aspect (Finney, 2002). For expressing fire intensity, RANDIG converts fireline intensity into flame length (Fl, m) by using the Byram's equation (Byram, 1959):

$$FL = 0.775\,(FI)^{0.046} \qquad \text{Eq. 3}$$

Then, the flame length distribution generated for each pixel by RANDIG is used to compute the conditional flame length (CFL, m) which is defined as:

$$CFL = \sum_{i=1}^{20} \left({}^{BP_i}/_{BP}\right)(F_i) \qquad \text{Eq. 4}$$

where F_i is the flame length midpoint of the ith category and BP is the burn probability. Attending to the equation 3, conditional flame length is defined as the probability weighted flame length give a fire occurs and measures fire hazard; in other words, it represents the average flame length registered for the simulated fires given a pixel (Ager et al., 2010).

4.2. Fire simulator inputs

For carrying out the fire simulations for the three scenarios with the software RANDIG, eight different inputs were needed. They were:

- Landscape file with .lcp extension
- Weather scenarios file with .txt extension
- Raster of ignitions in ASCII format
- Fuel model description file with .fmd extension
- Death and live fine fuel moisture file with .fms extension
- Dll of Flammap

- Randig 34
- Dll of Windninja

However, only the most important ones will be explained more specifically in the next epigraphs.

4.2.1. Landscape file (.LCP)

It contains the spatial features of the RNSM's landscape where wildfires were simulated. As well as in FARSIRE, the Landscape file used in RANDIG compiles eight different GIS raster layers in ASCII grid files that describe the fuels and topography (Finney, 2006b) (Figure 8). All spatial inputs assembled in Landscape file must have the same resolution, extent and co-registered (Finney, 2006b).

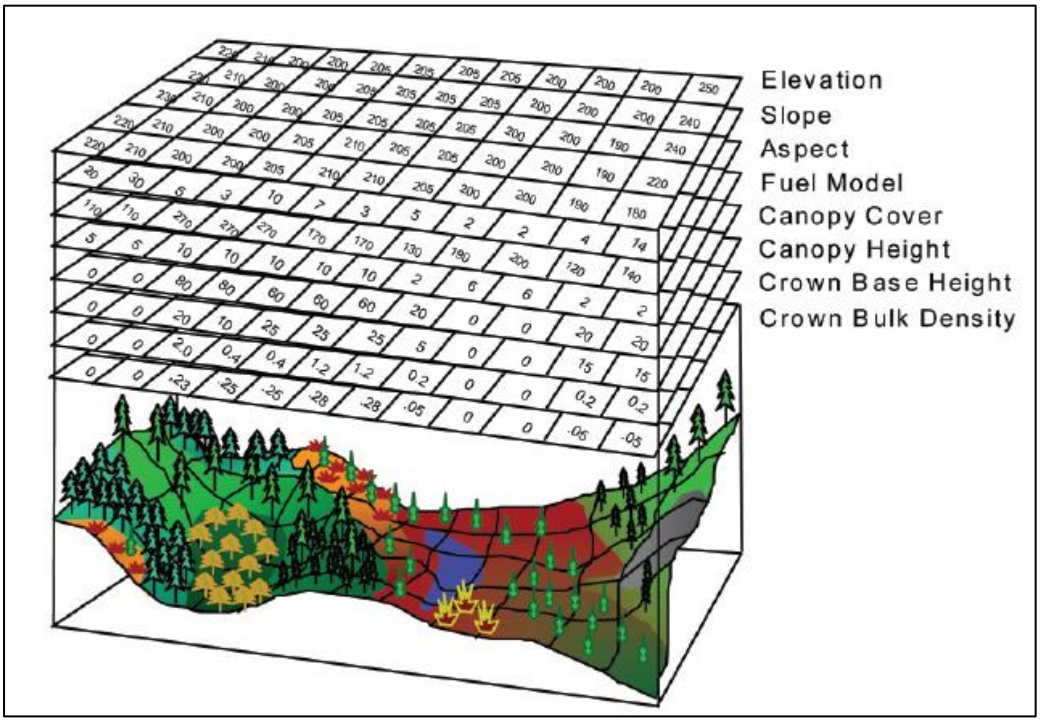

Fig 8. Input data themes needed to create Landscape file required for running RANDIG (same as FlamMap and FARSITE). All inputs are in ASCII format. (Finney, 2006b).

From the eight different spatial inputs: elevation, slope, aspect, fuel model, canopy cover, canopy height, crown base height and crown bulk density (Figure 6) at least 5 are necessary to run the simulation. Here elevation, slope, aspect, fuel model and canopy cover were used. Preparation of the data inputs for the Landscape files of the three different scenarios was done using the software ArcGIS 10.1.

The geo-referenced information used was provided from Grupo Portucel-Soporcel (gPS) and Instituto da Conservação da Natureza e das Florestas (ICNF).

Previously to the modelling exercise, it was necessary to select the GIS mapping coordinate system. From the different coordinate systems used in Portugal, the Datum PT-TM06-ETRS89 was chosen. This coordinate system was adopted by the Portuguese Geographic Institute (IGP) when Portugal joined the European network for terrestrial information (Direção-Geral do Território 2013). The adoption of this coordinate system instead of other ones more previously used for topographic purposes, such as Datum 73 or Datum Lisboa-Hayford Gauss, was justified because Datum PT-TM06-ETRS89 is being increasily used in Portugal whilst other systems are getting obsolete (Direção-Geral do Território, 2013). Therefore, all data was reprojected from the systems Datum 73 or Datum Lisboa-Hayford Gauss into Datum PT-TM06-ETRS89 using transformation grids with NTv2 format which seems to produce less transformation errors (Gonçalves, 2009).

Three different management scenarios, as described in next section, were then considered before the modelling exercise. Same spatial resolution with a pixel size of 90x90m and extent were used for all different management scenarios. Creation of the Landscape files was done by using FlamMap.

4.2.1.1. Scenario 0

Scenario 0 represents the current status of RNSM and was defined as a baseline scenario. Creation of a baseline scenario helps to understand the effects of other management treatments on the risk of wildfire in RNSM and Natura 2000 habitat types. As previously mentioned, for landscape creation five spatial inputs were used: elevation, slope, aspect, fuel model and canopy cover.

Elevation, slope and aspect

Elevation, slope and aspect inputs were obtained from a 90-m digital elevation model which in turn was gotten from the contour line *shapefile* of the study area. The units in which the raster-layers were computed were meters, percentage and degrees, respectively (Annex I).

Fuel model

In case of the fuel model input, this was interpreted by using the different Corine land cover (CLC) classes (EEA, 2007) contained in the land cover map of the area together with *in-situ* field observations. The characterization of fuel models using CLC classes has been used in previous works such as in Salis et al. (2013).

The creation of the CLC and fuel model *layers* for this scenario was done by joining the CLC and fuel model *layers* created for the area owned or managed by Grupo Portucel-Soporcel (gPS) together with the CLC and fuel model *layers* created for the remaining area. The complete process done for the creation of the layers is schematized diagrams in the Annex II.

The georeferenced data used for building the fuel model layer of the area non-managed by gPS was ceded by ICNF. For this task, the data used was the Carta de Ocupação de Ocupação e/ou Uso do Solo (COS) 2007 level 5 (IGeo, 2010) of the study area and the Carta de Vegetação (Instituto da Conservação da Natureza e das Florestas (ICNF), 2003) included in the management plan of RNSM and the Habitat Natural 2000 layer. The land cover and land use information contained by both georeferenced data was compared and results showed mismatching between both shapefiles. Many of these differences among both information sources are mostly related to the different creation date in which they were done since the Carta de Vegetação of RNSM and the COS 2007 date from the 2003 and 2007, respectively. So as a general rule, it was used the information contained by the COS2007 instead of the Vegetation *layer* because it was done more recently and more detailed in terms of vegetation composition and structure of the land cover and land uses.

However, there were some land cover and land uses classes where the COS2007 was representing them incorrectly or worse than the information given by the data of the management plan of RNSM. In these cases, the classes were overlapped, compared and mixed in order to obtain the most precise CLC *layer*. Land cover classes with matching problems were: Douglas-fir (*Pseudotsuga menziesii*), Black pine (*Pinus nigra*), Holm and Pyrenean oak (*Quercus rotundifolia* and *Quercus pyrenaica*), Strawberry tree (*Arbutus unedo*), Eucaliptus *spp*., “lameiros”, Mediterranean shrubland and Transitional shrub to woodland.

Special treatment was given to Strawberry tree (*Arbutus unedo*), Mediterranean shrubland and Transitional shrub to woodland classes. For the area occupied by Strawberry tree, the land cover was divided and classified in two different land cover classes because of the duality, shrub shape or tree shape, of this plant; so for humid areas, represented by north aspects, *Arbutus unedo* was assumed to have tree shape whereas the rest aspects were considered drier and assumed shrub shapes. Regarding to Mediterranean shrubland and Transitional shrub to woodland classes, they were treated paying attention to the dominant shrub species or group of species because it was needed as a previous step to after assign them the corresponding fuel model. Furthermore, as the COS2007 was only describing the biomass accumulation (dense or sparse) of the classes and the Vegetation *layer* was in many cases containing errors in the classification of the classes, a reclassification of the classes according to criteria based on *in-situ* observation was performed. As explained previously, the followed criteria assigned brooms (*Cytisus spp.*) as the dominant species in the north area of RNSM which corresponds to the area of the RNSM within the Sabugal municipality; for the rest of the area, it was assigned Heath (*Erica spp.*) - Carqueja (*Chamaespartium tridentatum)* as the dominant species for north aspects whereas Gum rockrose (*Cistus ladanifer*) was assigned to south exposures. The dominance of south exposure by Gum rockrose is justified as this pioneer species regenerates in low fertility soils.

As the CLC *layer* built from COS2007 and Vegetation *layers* represented the state of the RNSM at 2007, the interpretation of the fuel model from the land cover classes of the preserved area was going to be outdated. For that reason, the land cover classification of the scenario 0 was updated to 2015 by adding the forest road network, the burnt surfaces produced by fires, the treatments done in the managed areas and the fuel treatments accomplished by the fire management plan within RNSM.

Besides to the CLC *layer* of the area not managed by gPS, it was built another CLC layer of the area managed by them. It was chosen to do separately and after join together, because the information given by gPS was more precise and actual than the one given by the COS2007 and the Vegetation *layers*. Therefore, it was used the own land cover and land management gPS georeferenced information. As well as for the area outside of gPS zone, it was complete the information of the area updating the silvicultural treatments and fuel treatments done in order to get a better interpretation of the fuel models of the area. In a same way as previously, the Mediterranean shrubland class had a special treatment and it was distinguished the dominant shrub species following the same criteria used above.

Finally, both CLC *layers* were joined together. The total number of CLC classes in which RNSM was classified was 22 (Table 1). By percentage, transitional woodland-shrub and Mediterranean shrubland were the classes more dominant in the area, occupying the 25.32% and 31.24% of the area, respectively. They were followed by coniferous forest and broadleaves forest with 18.53% and 9.34% of the area. In contrast, many CLC classes were under the 1% such as non-irrigated arable lands, annual crops and so on. In case of fuel breaks and the forest road network (which also acts as a kind of fuel breaks) which were included in the class sparsely vegetated areas represented the 2.84% of the area.

Table 1. Corine Land Cover classes of the Natural Preserved area of Malcata and the percentage occupied by them in the scenario 0.

Corine Land Cover	CLC Description	Percentage occupied	Corine Land Cover	CLC Description	Percentage occupied
121	Industrial or commercial units	0.03%	312	Coniferous forest	18.53%
142	Sport and leisure facilities	0.01%	313	Mixed forest	2.03%
211	Non-irrigated arable land	0.04%	321	Natural grasslands	0.50%
212	Permanently irrigated land	0.81%	322	Moors and heathland (Mediterranean maquis)	31.24%
223	Permanent groves	0.05%	323	Sclerophyllous vegetation	5.2%
231	Pastures	1.50%	324	Transitional woodland-shrub	25.32%
241	Annual crops associated with permanent crops	0.44%	332	Bare rocks	0.02%
242	Complex cultivation patterns	<0.01%	333	Sparsely vegetated areas (fuel breaks & forest road network)	2.84%
243	Land principally occupied by agriculture, with significant areas of natural vegetation	<0.01%	334	Burnt areas	0.61%
244	Agro-forestry areas	0.16%	512	Water bodies	0.79%
311	Broadleaves forest	9.34%			

Once the Corine Land Cover *layer* of the preserved area was prepared (Figure 9), the different CLC classes were interpreted based in this classification and the fuel treatment applied during the last years.

Some of the CLC classes above described were divided in subclasses such as conifer forest in short-to-medium (*P. nigra* or *Pseudotsuga menziensii*) or medium-to-long needle size (*P. pinaster*), as broadleaves and Mediterranean shrublands in different classes according to the different species and its density (Table 2). The division was done in order to interpret the fuel models in a better way because although CLC classes assemble all species of a determinant class of plants *i.e.* conifers, broadleaves, shrubs; the species within a same group have different fire behavior.

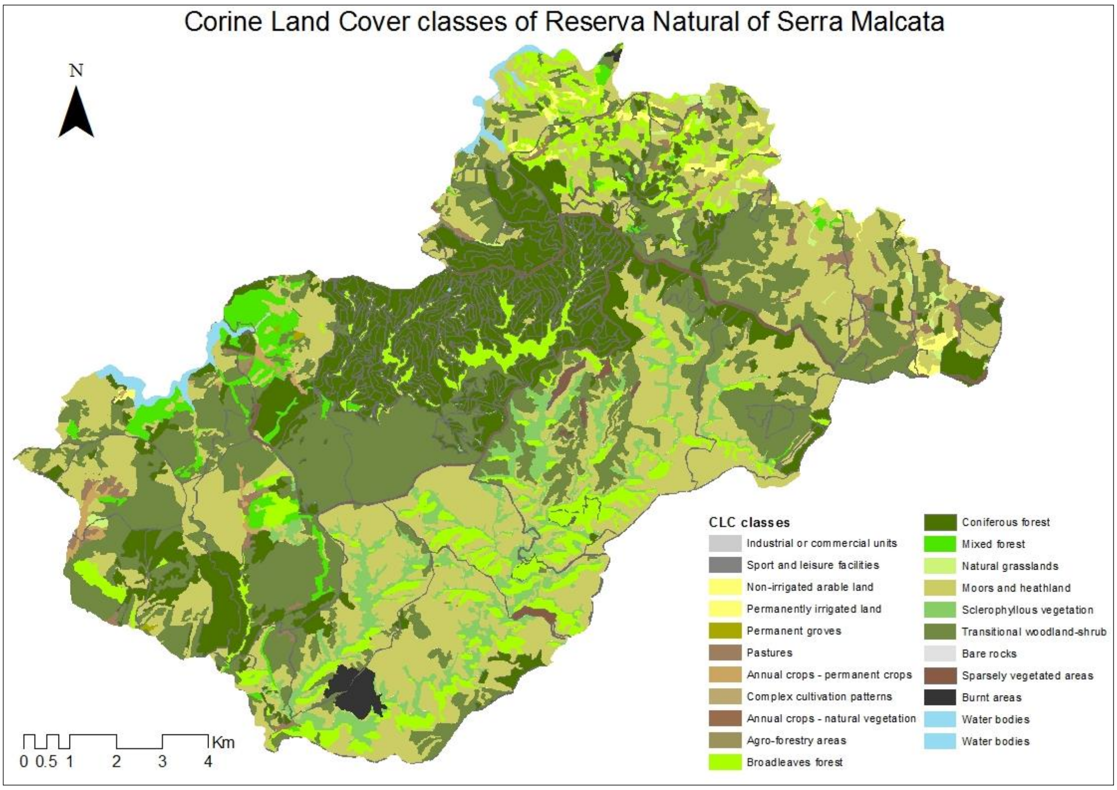

Fig 9. Corine Land Cover classes of Reserva Natural of Serra Malcata.

Table 2. Corine Land Cover classes and subclasses done for a better fuel model classification

Corine Land Cover	CLC Class Description	CLC subclassification
311	Broadleaves forest	Pyrenean oak (Q. pyrenaica)
		Holm oak (Q. rotundifolia), Pyrenean oak (Q. pyrenaica) and Strawberry tree (Arbutus unedo)
		Eucaliptus spp.
		Strawberry tree (Arbutus unedo)
		Chestnut (C.sativa)
312	Coniferous forest	Black pine (P.nigra)
		Douglas-fir (Pseudotsuga menziensii)
		Maritime pine (P. pinaster)

313	Mixed forest		Eucaliptus spp. - Conifers
			Maritime pine (P. pinaster) - Holm oak (Q. rotundifolia), Pyrenean oak (Q. pyrenaica) and Strawberry tree (Arbutus unedo)
			Maritime pine (P. pinaster) - Pyrenean oak (Q. pyrenaica)
			Holm oak (Q. rotundifolia) - Maritime pine (P. pinaster)
			Maritime pine (P. pinaster) - Chestnut (C.sativa)
322	Moors and heathland (Mediterranean maquis)	Dense	Brooms (Cytisus spp.)
			Gum rockrose (Cistus ladanifer)
			Heath (Erica spp) - Carquesia (Chamaespartium tridentatum)
		Sparse	Brooms (Cytisus spp.)
			Gum rockrose (Cistus ladanifer)
			Heath (Erica spp) - Carquesia (Chamaespartium tridentatum)
324	Transitional woodland-shrub		Pyrenean oak (Q. pyrenaica) - Brooms (Cytisus spp.)
			Strawberry tree (Arbutus unedo) - Chestnut (C.sativa) - Brooms (Cytisus spp.)
			Holm oak (Q. rotundifolia) - Strawberry tree (Arbutus unedo) - Brooms (Cytisus spp.)
			Holm oak (Q. rotundifolia) - Strawberry tree (Arbutus unedo) - Gum rockrose (Cistus ladanifer)
			Holm oak (Q. rotundifolia) - Strawberry tree (Arbutus unedo) - Heath (Erica spp) & Carquesia (Chamaespartium tridentatum)
			Conifers - Broadleaves - Brooms (Cytisus spp.)
			Conifers - Broadleaves - Gum rockrose (Cistus ladanifer)
			Conifers - Broadleaves - Heath (Erica spp) & Carquesia (Chamaespartium tridentatum)
			Maritime pine (P. pinaster) - Brooms (Cytisus spp.)
			Maritime pine (P. pinaster) - Gum rockrose (Cistus ladanifer)
			Maritime pine (P. pinaster) - Gum rockrose (Cistus ladanifer)
			Maritime pine (P. pinaster) - Heath (Erica spp) & Carquesia (Chamaespartium tridentatum)
			Clear cuts

The fuel model types assigned to each land cover type came from a set of custom fuel models developed for Portugal (Fernandes et al., 2009). The fuel models are defined by the main driver of the fire behavior which is defined according to the structure and the relative abundance of tree litter and understory vegetation (Fernandes et al., 2009). So fuel models designed as *Folhada (F)* are fuel models where tree litter is the main driver; when fire is driven by the understory, it is classified as *Vegetação (V)* and when fire is driven by both, then, it is classified as *Misto (M)*. Using these criteria, thirteen of the total eighteen custom fuel models were defined from the land cover classes of the preserved area (Table 3). However, it was needed to relate the custom fuel models of Portugal with Farsite fuel models for being able to running the simulations. Relationships were done according to the relations that were established by (Fernandes et al., 2009).

Table 3. Fuel models of RNSM, their relationships with the different land cover classes and the percentage occupied by them in the scenario 0.

Corine Land Cover	Fuel model (Farsite)	Fuel model (Portugal)	Fuel model description	Percentage occupied
Artificial surfaces/Agricultural crops/Permanently irrigated crops/Rock outcrops/Sparsely vegetated areas/Burnt areas/Water bodies	99	No burn	Bare soil, little or no vegetation, rocks, constructions or water bodies	4.27%
Chestnut (Managed stands)	212	F-FOL	Tree litter with shrub understory (usually big amount of living fuel load) (2-5 t/ha)	0.07%
Maritime pine (Managed stands of gPS area)	213	F-PIN	Compact pine litter of medium to large needle size (4-7 t/ha)	0.26%
Black pine & Douglas fir (Managed stands of gPS area)	214	F-RAC	Compact pine litter of short to medium needle size (4-6 t/ha)	3.65%
Chestnut forest/Pyrenean oak forest/Mixed forest dominated by Pyrenean oak	221	M-CAD	Tree litter with shrub understory (usually big amount of living fuel load) (8-17 t/ha)	4.14%
Eucalyptus (Managed forest)	224	M-EUCd	Discontinuous eucalyptus litter with or no understory in the plantation lines (1-4 t/ha)	0.08%
Black pine & Maritime pine (Managed areas of gPS or other where treatments did not produce adequate results)	227	M-PIN	Pine litter and woody understory (8-18 t/ha)	6.03%
Non-irrigated arable land/Agroforestry lands/Permanent pastures/Natural grasslands/Annual crops/Olive crops	232	V-Hb	Low grass (<0.5 m) (1-1 t/ha)	3.01%
Dense Mediterranean shrubs dominated by Heath-Carquesia/Mixed forest Eucalyptus-Conifers/ Eucalyptus (old non-managed forest)	233	V-MAa	Tall shrubs (>1m), dead fuels are important (12-27 t/ha)	10.26%
Black pine & Maritime pine & Douglas fir (non-managed)/ Dense (treated) & Sparse Mediterranean shrubs dominated by Heath-Carquesia/ Transitional woodland-shrub of any tree association with understory dominated by Heath-Carquesia	234	V-MAb	Low shrubs (<1 m), dead fuels are important (7-14 t/ha)	11.39%
Any recent treated shrubland or forest with prescribed fire	235	V-MH	Low shrubs (<1 m) and green, usually discontinuous	5.44%

Dense Mediterranean shrubs dominated by Brooms or Gum rockrose/ Sclerophyllus vegetation (*A. unedo*) (well developed)	236	V-MMa	Tall shrubs (>1m), dead fuels are not important (10-19 t/ha)	27.37%
Dense (treated) & Sparce Mediterranean shrubs dominated by Brooms or Gum rockrose/ Holm oak and Strawberry tree/ Mixed forest with dominance of Holm oak and Strawberry tree over conifers/ Mixed forest Maritime pine and Chestnut/ Transitional woodland-shrub of any tree association with understory dominated by Brooms or Gum rockrose/ Clear cuts	237	V-MMb	Low shrubs (<1 m), dead fuels are not important (4-8 t/ha)	24.07%

Land cover classes related to artificial surfaces, fuel breaks and forestall road network, agricultural crops, recent burnt areas and water bodies were classified as No burn area. Same conifer and broadleaves land cover classes such as Maritime pine, Black pine, Douglas-fir or Pyrenean oak were classified in different fuel model classes according to if they were managed; so following this criteria, area non-managed were classified with fuel models where fire is driven by both tree litter and understory vegetation. On the other hand, the classification of *P. nigra* and *P. pinaster* forest of managed areas into fuel model was more difficult. By *in-situ* observations within the managed area, it was observed that different fuel models could be used for the same pure stands in areas where vegetation management had been implemented since 2007. However, it was impossible to differentiate fuel models according to the year when treatments were implemented by assigning fuel models with more fuel load to areas where treatments were implemented previously and *vice versa* because the distribution of stands according to this criterion did not match. So, fuel models were assigned randomly in order to have less *bias*. Therefore, managed areas were described by fuel models type *Folhada* or *Misto*, meanwhile, non-managed land cover classes where classified with models where understory vegetation is the main driver.

Natural grasslands, permanent pastures, agroforestry areas and other kind of agricultural areas were classified with fuel model V-Hb in which vegetation is the main driver. Mediterranean maquis and Transitional shrub to woodland were classified with fuel models in which vegetation was also the main driver. For Mediterranean shrubland classes, it was differentiated between vegetation dominant shrubs due to its different fire behavior and according the density of the plant shrub population. Areas dominated by dense or sparse populations Brooms (*Cytisus spp.*) or by Gum rockroses (*Cistus ladanifer*), which do not retain so much dead fine fuels, took fuel models V-MMa and V-MMb, respectively. These are fuel models which are differentiated in the quantity of fuel load. For areas dominated by dense or sparse populations of Heath (*Erica spp.*) & Carqueja (*Chamaespartium tridentatum*), which retain so much dead fine fuels, took fuel models V-MAa and V-MAb, respectively. They were differentiated following the same criteria as described above. In case of Transitional shrub to woodland, it was followed the same criteria as before; it was designated as V-MMb or V-MAb according to the dominant understory specie independently of the tree species. In addition, it was used V-MMb and V-MAb fuel models for previous dense shrubland which had been treated and for Holm oak – Strawberry tree forest which had a dense understory below their canopies. Finally, it was assigned fuel model type V-MH to areas recently treated.

Fuel models classes within RNSM (Figure 10) appeared in different proportions (Table 3), fuel models V-MMa, V-MMb, V-MAb and V-MAa were the most representative of RNSM with 27.34%, 24.07%, 11.39% and 10.26% meanwhile M-EUCd, F-FOL and F-PIN were the less present with 0.08%, 0.07% and 0.26%, respectively.

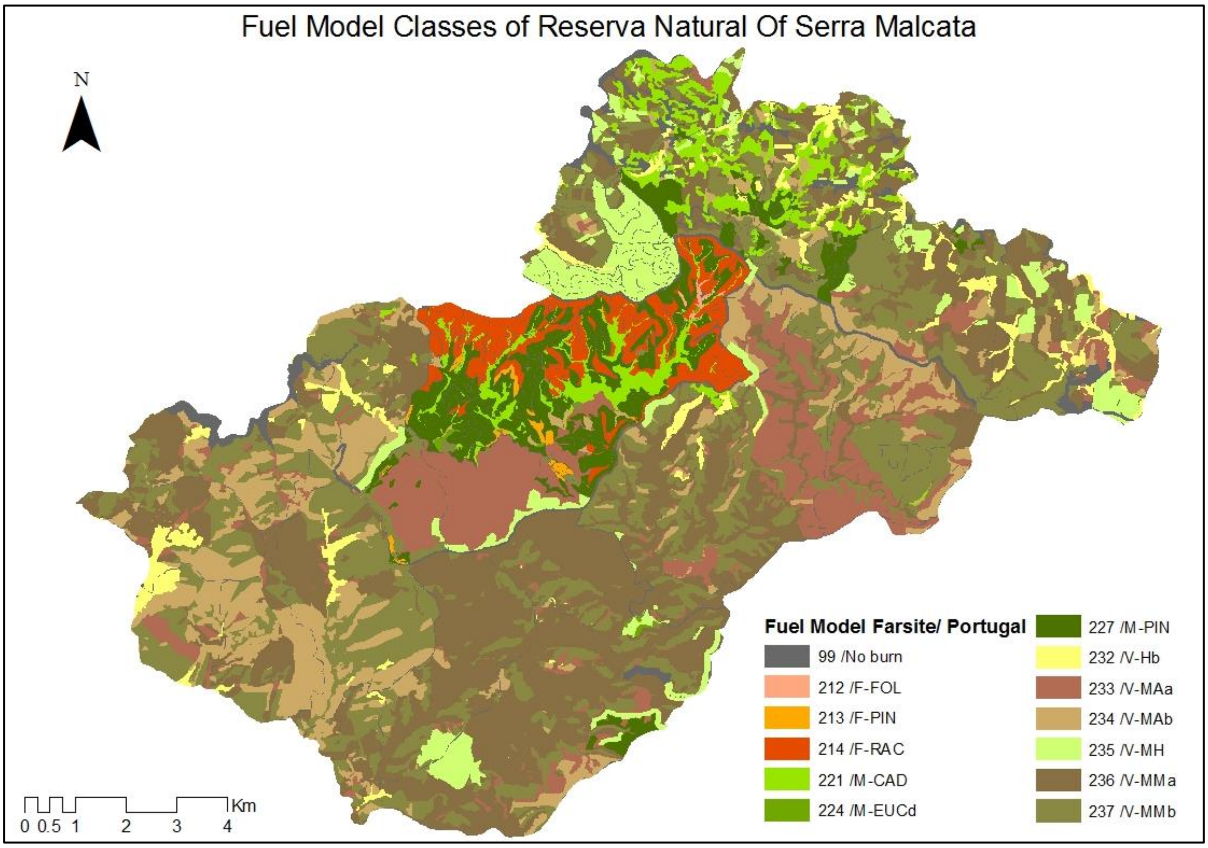

Fig 10. Fuel model types of RNSM according to Farsite number and its correspondent Portuguese custom fuel model for Scenario 0.

Canopy cover

The canopy cover *layer* was built (Figure 11) using the Corine Land Cover classes above described. Its characterization was based on the canopy cover information of COS 2007 and through *in-situ* observations within the area.

The values assumed (Table 4) varied from 0 % of the areas occupied by Mediterranean shrubs, water bodies, grasslands, artificial surfaces and agricultural crops to the 84% and

85% of the areas cover by eucalyptus stands and Douglas fir forests, respectively. Areas covered by conifer forests had values of 44% for Maritime pine stands and 60% for Blank pine and other pine species. Transitional shrub to woodland took values of 20% which represents the value of transition from one to the other land cover state described by COS 2007. Broadleaves areas had values that went from the 30% of the Sclerophyllous broadleaves to the 50% represented by Chestnut or Pyrenean oak forest.

Table 4. Canopy cover of RNSM area related to Corine Land Cover classes and the percentage cover by them.

Corine Land Cover classes	Canopy cover (%)	Percentage occupied
Artificial surfaces/Agricultural crops/Permanently irrigated crops/Rock outcrops/Sparsely vegetated areas/Burnt areas/Water bodies/ Non-irrigated arable land /Permanent pastures/Natural grasslands/Annual crops/Olive crops/ Dense & Sparce Mediterranean shrubs dominated by Brooms or Gum rockrose/ Dense & Sparse Mediterranean shrubs dominated by Heath-Carquesia/ Clear cuts	0	44.20%
Agroforestry	10	0.17%
All type transitional shrub to woodland	20	25.29%
Sclerophyllous broadleaves (Holm oak – Strawberry tree)	30	4.38%
Maritime pine forests/ Mixed forest Conifers (Dominance) – Eucalyptus *spp.*	44	8.31%
Mixed forest Conifers (Dominance) – Sclerophyllous vegetation	45	2.05%
Chestnut forest/ Pyrenean oak forest/ Mixed forest Broadleaves (Dominance) – Conifers	50	4.36%
Mixed forest Conifers (Dominance) – Broadleaves/ Maritime pine-other type of conifer/ Black pine forest/ Other pine type forest	60	6.82%
Eucalyptus *spp.*	84	0.80%
Douglas fir forest	85	3.62%

Regarding to the area occupied by each canopy cover class, there were two classes which stand out over the other (Table 4). Canopy cover classes of 0% and 20% represented the 44.20% and 25.29%, respectively. On the other hand, classes 10% and 84% were the less represented with 0.17% and 0.80%. In general, the preserved area of Serra Malcata had low values of canopy cover; this is caused by the fact that shrubs and transitional shrub to woodland classes are the most extent in the area of study.

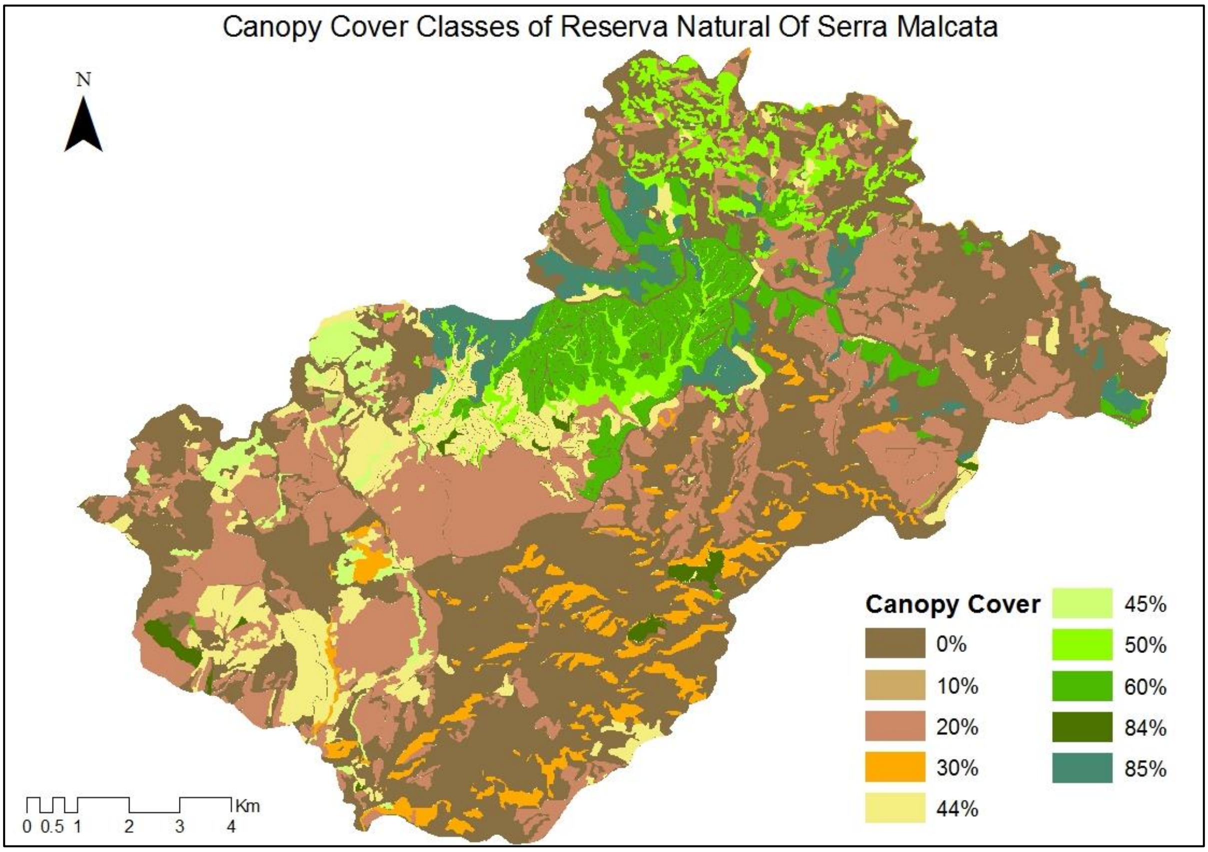

Fig 11. Canopy cover classes of Reserva Natural of Serra Malcata for Scenario 0.

4.2.1.2. Scenario 1

Scenario 1 represents the situation of the preserved area of Serra Malcata if the fuel treatments designed by the different fire management plans were done. These plans are usually for a period of years; however, for simplifying the creation of the Scenario 1, it was assumed all treatments were going to be applied at the same time. As well as in the Scenario 0; it was needed to obtain the elevation, aspect, slope, fuel model and canopy cover in ASCII format for the creation of the landscape file.

Elevation, slope and aspect

As well as for Scenario 0, elevation, slope and aspect inputs were obtained following the same process above described. The units in which the raster-layers were computed were meters, percentage and degrees, respectively.

Fuel model

Fuel model shapefile of the Scenario 1 was created by updating the Scenario 0 with the fuel treatments projected on the Fire Managament plan of the municipality of Sabugal for the years 2014 to 2018, the Prescribed Fire plan of RNSM from 2014 to 2018 and the prospect Fire Management actions within the area managed by GPS company. The Fire Management plan of Penamacor was impossible to use for building the Scenario 1 because it had not been approved yet.

The construction of the fuel model shapefile for the Scenario 1 was done separately for the areas managed and non-managed by gPS. After that, they were joined together. The total area treated was approximately 2,111 ha which accounts for the 13% of the total area (Figure 12). Ideally, I had preferred to do treatments of the 20% (3269.6 ha) of the area which had been seen to be the most effective for reducing wildfire risk in other preserved areas (Ager et al., 2007). However, as the Fire Management plan of Penamacor was not approved yet; it was treated the extension previously commented.

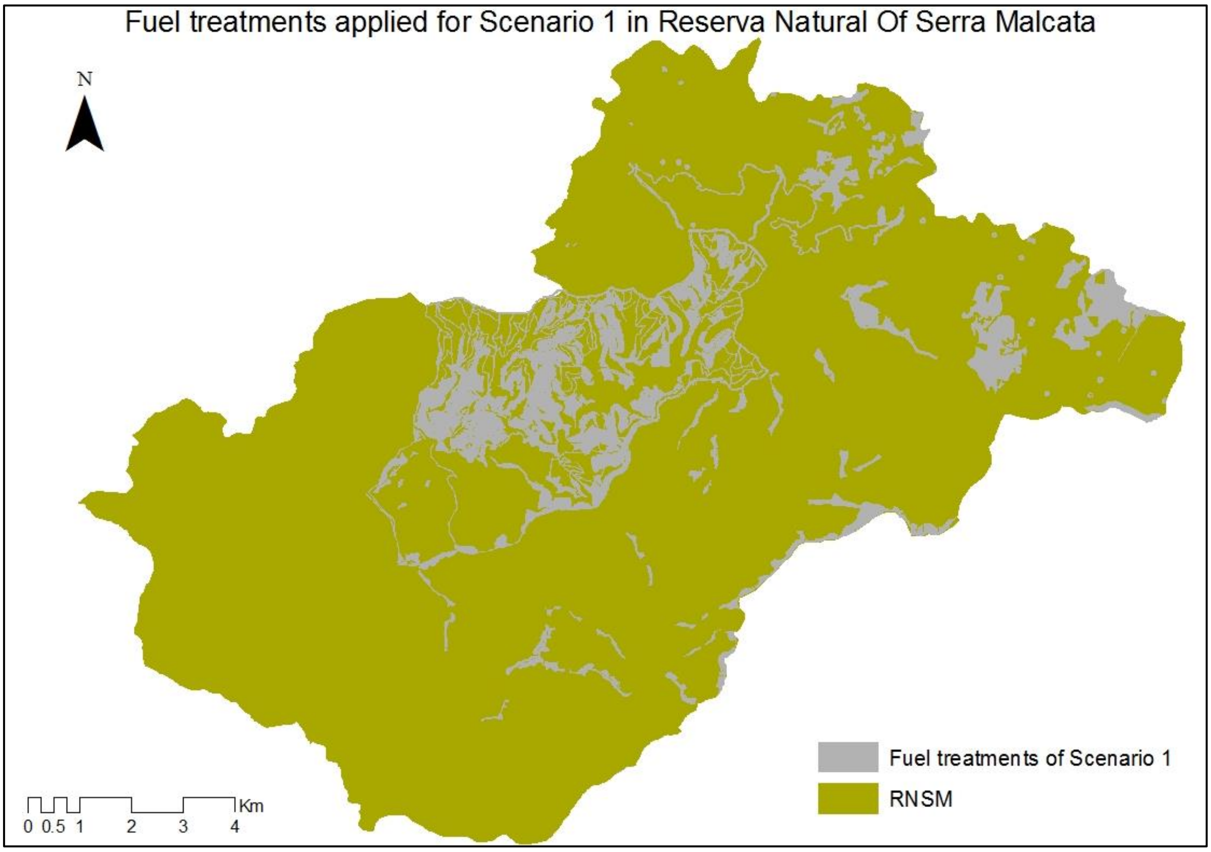

Fig 12. Fuel treatments applied for the Scenario 1 in the preserved area of Serra Malcata.

For the area non-managed by gPS, the surface treated projected by the different plans was 868 ha. For the creation of the Scenario 1 in this area, it was used the *layers* FGC_Sabugal.shp and PFC_AltoCoa_Malcata.shp. Regarding to the area managed by gPS, the fire management actions were focus on keeping the fuel break network and thinning softwood stands. The first action was done by maintaining the forestry road network (which acts as fuel breaks) and fuel breaks and by creating a buffer of 10m around the forestry road and fuel break network. In addition, it was executed thinning actions in the softwoods stands with higher fuel loads represented by fuel models 227 or M-PIN. The total surface treated within gPS area was 1,101 ha from which the maintenance of the fuel break network was

504 ha meanwhile thinning's accounted for 597 ha. More information of the process followed in the GIS software can be consulted in the diagrams contained in the Annex III.

The number of fuel models classes present in the Scenario passed from 13 classes to 14 classes (Figure 13). The most representative fuel models were by far the classes 237 and 236 with 23.23% and 25.83%, respectively. After those classes, fuel models 234 and 233 where the most representative. The class 232 and the new fuel model class, the 226, represented the 6.08% and 7.04% which increased as a result of the fuel treatments. The fuel models classes less represented, as in the Scenario 0, were M-EUCd, F-FOL and F-PIN with 0.08%, 0.07% and 0.19%, respectively (Table 5).

Table 5. Fuel models of RNSM and the percentage occupied by them in the scenario 1.

Fuel model (Farsite)	Fuel model (Portugal)	Fuel model description	Percentage occupied
99	No burn	Bare soil, little or no vegetation, rocks, constructions or water bodies	4.27%
212	F-FOL	Tree litter with shrub understory (usually big amount of living fuel load) (2-5 t/ha)	0.07%
213	F-PIN	Compact pine litter of medium to large needle size (4-7 t/ha)	0.19%
214	F-RAC	Compact pine litter of short to medium needle size (4-6 t/ha)	2.89%
221	M-CAD	Tree litter with shrub understory (usually big amount of living fuel load) (8-17 t/ha)	3.95%
224	M-EUCd	Discontinuous eucalyptus litter with or no understory in the plantation lines (1-4 t/ha)	0.08%
226	M-H	Litter and grass (2-5 t/ha)	7.04%
227	M-PIN	Pine litter and woody understory (8-18 t/ha)	1.37%
232	V-Hb	Low grass (<0.5 m) (1-1 t/ha)	6.08%
233	V-MAa	Tall shrubs (>1m), dead fuels are important (12-27 t/ha)	9.41%
234	V-MAb	Low shrubs (<1 m), dead fuels are important (7-14 t/ha)	10.88%
235	V-MH	Low shrubs (<1 m) and green, usually discontinuous	4.70%
236	V-MMa	Tall shrubs (>1m), dead fuels are not important (10-19 t/ha)	25.83%
237	V-MMb	Low shrubs (<1 m), dead fuels are not important (4-8 t/ha)	23.23%

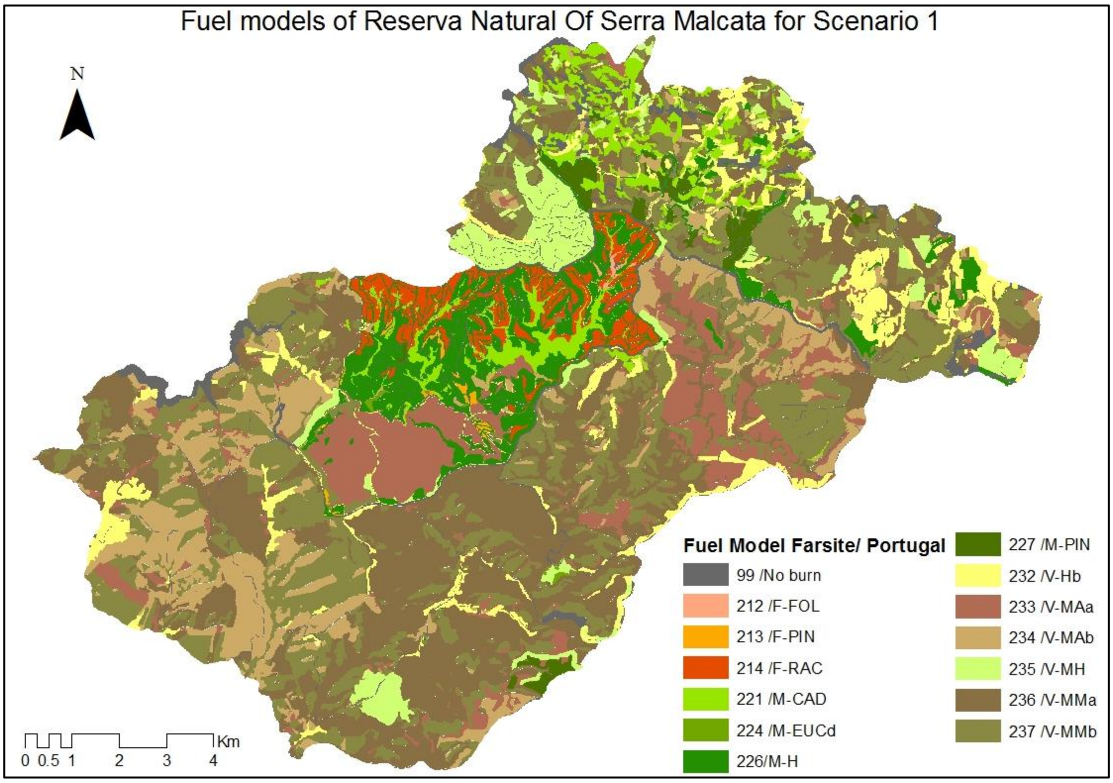

Fig 13. Fuel model types of RNSM according to Farsite number and its correspondent Portuguese custom fuel model for Scenario 1.

The fuel treatments done for the scenario 1 resulted in fuel models with low fuel loads represented by 226 for woodlands and 232 for shrublands. Table 6 contains the relationships of fuel models between the Scenario 0 and Scenario 1. Forestry road and fuel break network kept the same fuel model class because of the maintenance.

Table 6. Fuel treatments done in the Scenario 1 and relationships between the fuel models of the Scenario 0 and Scenario 1 affected by the treatments.

Fuel treatments		Fuel model Scenario 0	Fuel model Scenario 1
Forestry road network & Fuel breaks network		99/ No burn	99/ No burn
Buffer 10m each side	Maritime pine	227/ M-PIN	226/ M-H
	Black pine	227/ M-PIN	
	Douglas-fir	214/ F-RAC	
	Dense Mediterranean shrub	236 or 233/ V-MMa or V-MAa	232/ V-Hb
	Sparse Mediterranean shrub	237 or 234/ V-MMb or V-MAb	
	Transitional shrub to woodland	237 or 234/ V-MMb or V-MAb	
Softwoods treatments & other treatments	Maritime pine	227/ M-PIN	226/ M-H
	Black pine	227/ M-PIN	
	Douglas-fir & Mediterranean shrub	237/ V-MMb	
	Transitional shrub to woodland	237 or 234/ V-MMb or V-MAb	

Canopy cover

As well as the decrease of fuel load of the treated areas, fuel treatments produced changes in the canopy cover of the treated areas (Figure 14). As shows the table 7, conifer's land covers took values of 20% on buffer areas meanwhile it took 30%, 45% and 45% in areas where thinnings were done. Transitional shrub to woodland and Mediterranean maquis continued having same values.

Table 7. Fuel treatments done and the canopy cover changes relationships between target land cover classes of the Scenario 0 and Scenario 1.

<table>
<tr><th colspan="2">Fuel treatments</th><th>Canopy cover Scenario 0</th><th>Canopy cover Scenario 1</th></tr>
<tr><td colspan="2">Forestry road network & Fuel breaks network</td><td>0%</td><td>0%</td></tr>
<tr><td rowspan="6">Buffer 10m each side</td><td>Maritime pine</td><td>44%</td><td rowspan="3">20%</td></tr>
<tr><td>Black pine</td><td>60%</td></tr>
<tr><td>Douglas-fir</td><td>85%</td></tr>
<tr><td>Dense Mediterranean shrub</td><td>0%</td><td rowspan="2">0%</td></tr>
<tr><td>Sparse Mediterranean shrub</td><td>0%</td></tr>
<tr><td>Transitional shrub to woodland</td><td>20%</td><td>20%</td></tr>
<tr><td rowspan="4">Softwoods treatments & other treatments</td><td>Maritime pine</td><td>44%</td><td>30%</td></tr>
<tr><td>Black pine</td><td>60%</td><td>45%</td></tr>
<tr><td>Douglas-fir & Mediterranean shrub</td><td>85%</td><td>30%</td></tr>
<tr><td>Transitional shrub to woodland</td><td>20%</td><td>20%</td></tr>
</table>

The number of canopy cover classes for both Scenarios 0 and 1 were the same but the extent of the different classes changed. However, these changes did not affect the previous distribution explained above. Canopy cover classes 0% and 20% continued being ones with more extension as well as 10% and 84% were the ones with less extent (Table 8).

Table 8. Canopy cover classes and their extension in Scenario 1 of the preserved area of Serra Malcata.

Canopy cover (%)	Percentage occupied
0	44.20%
10	0.16%
20	27.03%
30	6.11%
44	6.04%
45	4.00%
50	4.36%
60	3.97%
84	0.80%
85	3.31%

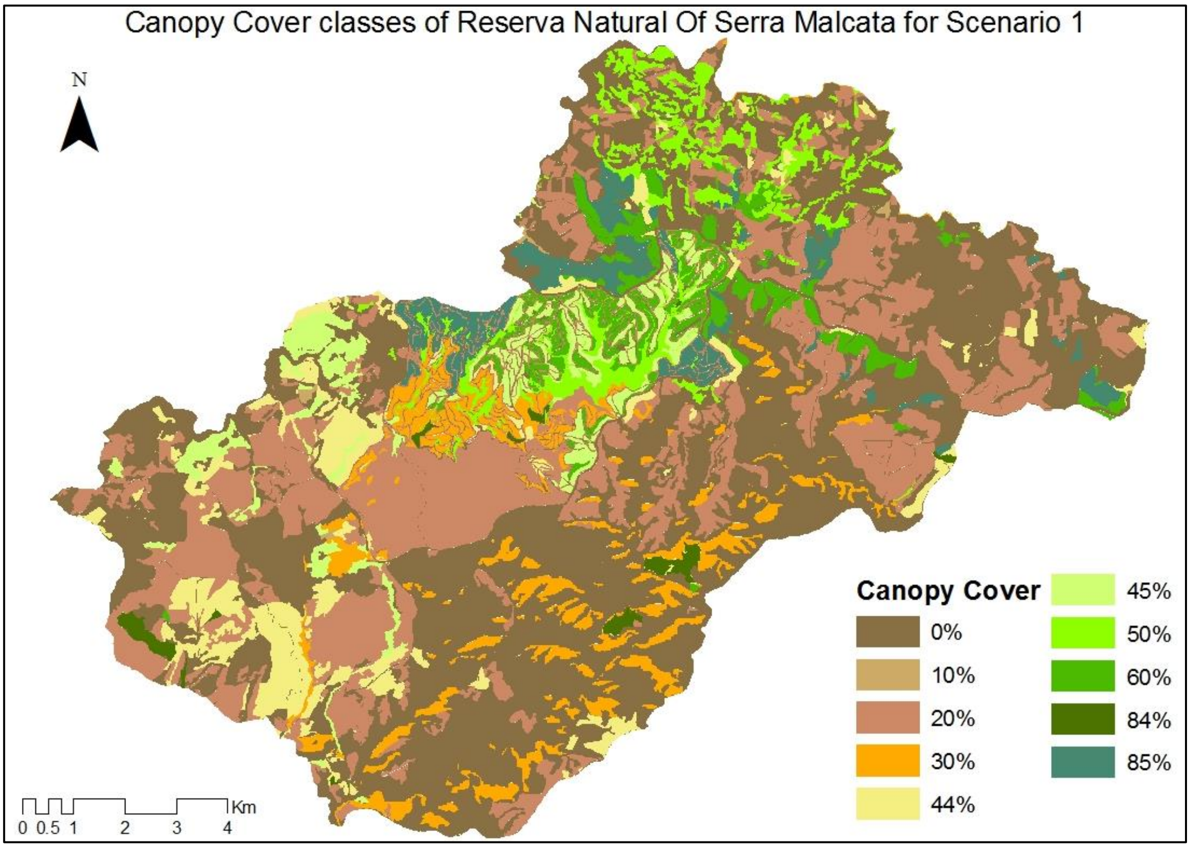

Fig 14. Canopy cover classes for Scenario 1 in RNSM.

4.2.1.3. Scenario 2

In Scenario 2, fuel treatments were designed in order to maximize conservation of different Natura 2000 habitat types simultaneously reducing fire exposure. For achieving this, it was decided to do fuel treatments inside of Natura 2000 habitat types, a completely forbidden action in some of these habitat types such as habitats 9340 (*Q. ilex* and *A. unedo* forest) or 9230 (Galaico-portuguese oak-woods with dominance of *Q. pyrenaica*) (Instituto da Conservação da Natureza e das Florestas (ICNF), 2003). As well as for Scenario 1, treatments were applied at same time in order to simplify the design of the Scenario 2. Same inputs in ASCII format were required for creating the landscape file of the Scenario 2. More information of the process followed in the GIS software can be consulted in the diagrams contained in the Annex IV.

<u>Elevation, slope and aspect</u>

Raster files used for Scenario 0, with information on elevation, slope and aspect were used for scenario 2. The units in which the raster-layers were computed were meters, percentage and degrees, respectively.

Fuel model

Fuel model *layer* of Scenario 2 was created by updating the fuel model *layer* of the Scenario 0 with fuel treatments designed with the aim of maximizing conservation goals and reducing fire exposure. Contrary to previous scenarios, the design of this one was done without any property discrimination. In order to achieve the objectives mentioned above, it was designed different fuel treatments which surface treated would be around 2,150 ha (Figure 15) which is similar to the surface area treated in the Scenario 1 (2,111 ha).

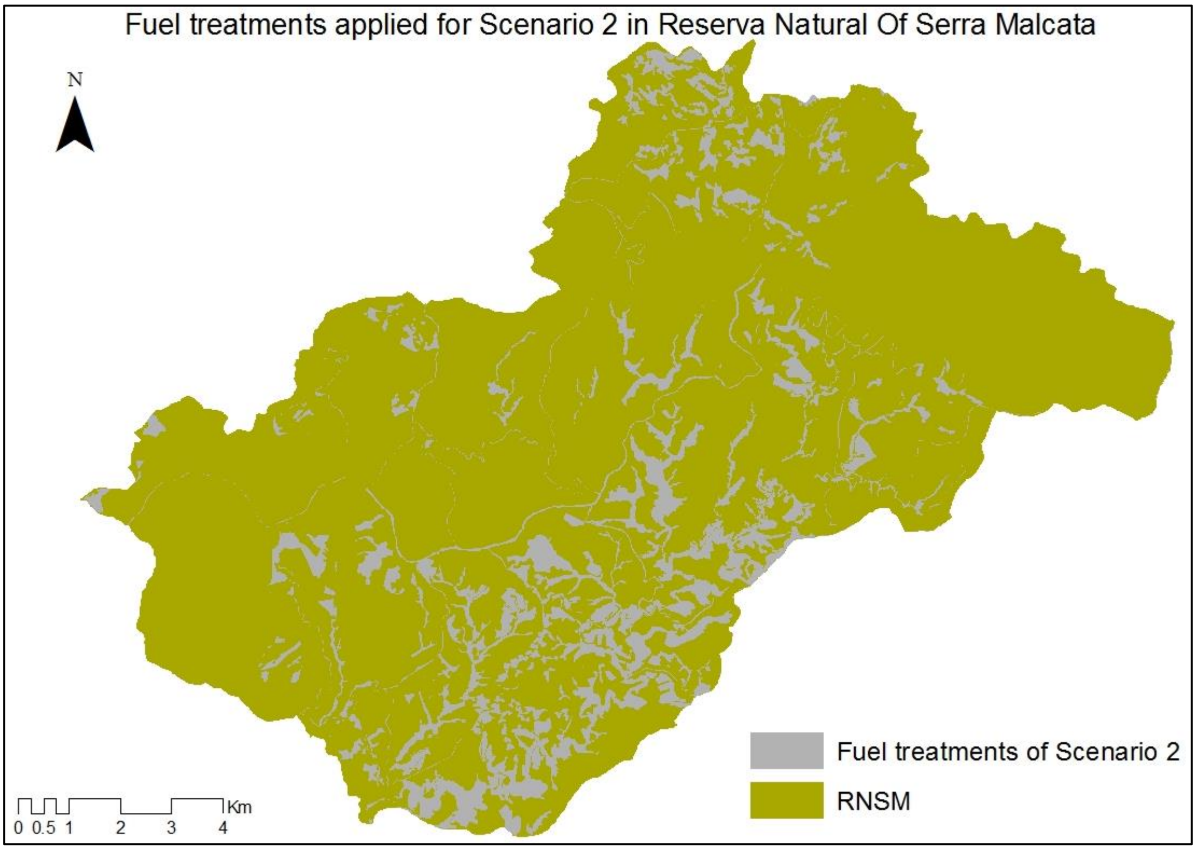

Fig 15. Location of the fuel treatments applied in RNSM for the design of the Scenario 2.

The designing of the Scenario 2 was done following two main ideas. The first one was to introduce fuel treatments actions within Natura 2000 habitat types; these, which *a priori* could produce a minimal loss of the ecosystem values, could revert to a bigger decrease of fire exposure than Scenario 1 while it would be maximizing conservation goals in a medium to long-term. The selected Natura 2000 habitat types for being treated were habitats 9230, 9340, 5330 where fuel treatments are forbidden and 4030 where fuel treatments have done already. The selection of the areas within the different Natura 2000 habitat types was done following a criteria based on the localization, composition and previous fuel model. In addition to that, it was tried to select areas located in a way that fuel treatment produced a mosaic landscape structure, supplying heterogeneity to the landscape. The total extension treated within Natura 2000 areas were 1687 ha.

The selected fuel treatment applied within Natura 2000 Habitats was prescribed burning which consist on low intense control burning of fuel biomass. This kind of fuel treatment is world wide spread and temporarily decreasing of potential fire intensity and suppression difficulties have been demonstrated (Agee and Skinner, 2005; Fernandes and Botelho, 2003).

Secondly, I decided to maintain the forestry road and fuel break network and to improve its role against wildfire by creating a buffer of 15m to each side. The target roads and fuel breaks were selected according to their localization related to Natura 2000 habitat types and by their location inside of RNSM; that is, taking into account if they were dividing the different Natura 2000 habitat types by sub-watershed with the aim to facilitate fire contention and avoid its spread from Natura 2000 habitat types of one sub-watershed to another. In this case the area related to forestry road and fuel break network treated was 463.17 ha.

The number of fuel model classes of the Scenario 2 was 14 (Figure 16), the same classes as in Scenario 1. As well as in the scenarios above described, the fuel model classes with more extension were by far the classes 237 and 236 with 26.82% and 20.69%, respectively (Table 9). However, in contrast to the previous Scenarios 0 and 1, Scenario 2 has reverted the general tendency and fuel model 237 with less fuel load was in bigger proportion than fuel model 236 with more fuel load. The fuel models classes M-EUCd, F-FOL and F-PIN with 0.09%, 0.07% and 0.25%, respectively continued to be the less present in the area. In case with fuel models 226 and 227, they changed also their percentage of occupancy in RNSM reaching the 2.90% and 5.89%, respectively; what contrast with the percentages in the Scenario 1 which were 70.4% and 1.37%.

Table 9. Fuel models of RNSM and the percentage occupied by them in the Scenario 2.

Fuel model (Farsite)	Fuel model (Portugal)	Fuel model description	Percentage occupied
99	No burn	Bare soil, little or no vegetation, rocks, constructions or water bodies	4.33%
212	F-FOL	Tree litter with shrub understory (usually big amount of living fuel load) (2-5 t/ha)	0.07%
213	F-PIN	Compact pine litter of medium to large needle size (4-7 t/ha)	0.25%
214	F-RAC	Compact pine litter of short to medium needle size (4-6 t/ha)	3.57%
221	M-CAD	Tree litter with shrub understory (usually big amount of living fuel load) (8-17 t/ha)	2.01%
224	M-EUCd	Discontinuous eucalyptus litter with or no understory in the plantation lines (1-4 t/ha)	0.09%

226	M-H	Litter and grass (2-5 t/ha)	2.90%
227	M-PIN	Pine litter and woody understory (8-18 t/ha)	5.89%
232	V-Hb	Low grass (<0.5 m) (1-1 t/ha)	7.83%
233	V-MAa	Tall shrubs (>1m), dead fuels are important (12-27 t/ha)	9.41%
234	V-MAb	Low shrubs (<1 m), dead fuels are important (7-14 t/ha)	11.00%
235	V-MH	Low shrubs (<1 m) and green, usually discontinuous	5.13%
236	V-MMa	Tall shrubs (>1m), dead fuels are not important (10-19 t/ha)	20.69%
237	V-MMb	Low shrubs (<1 m), dead fuels are not important (4-8 t/ha)	26.82%

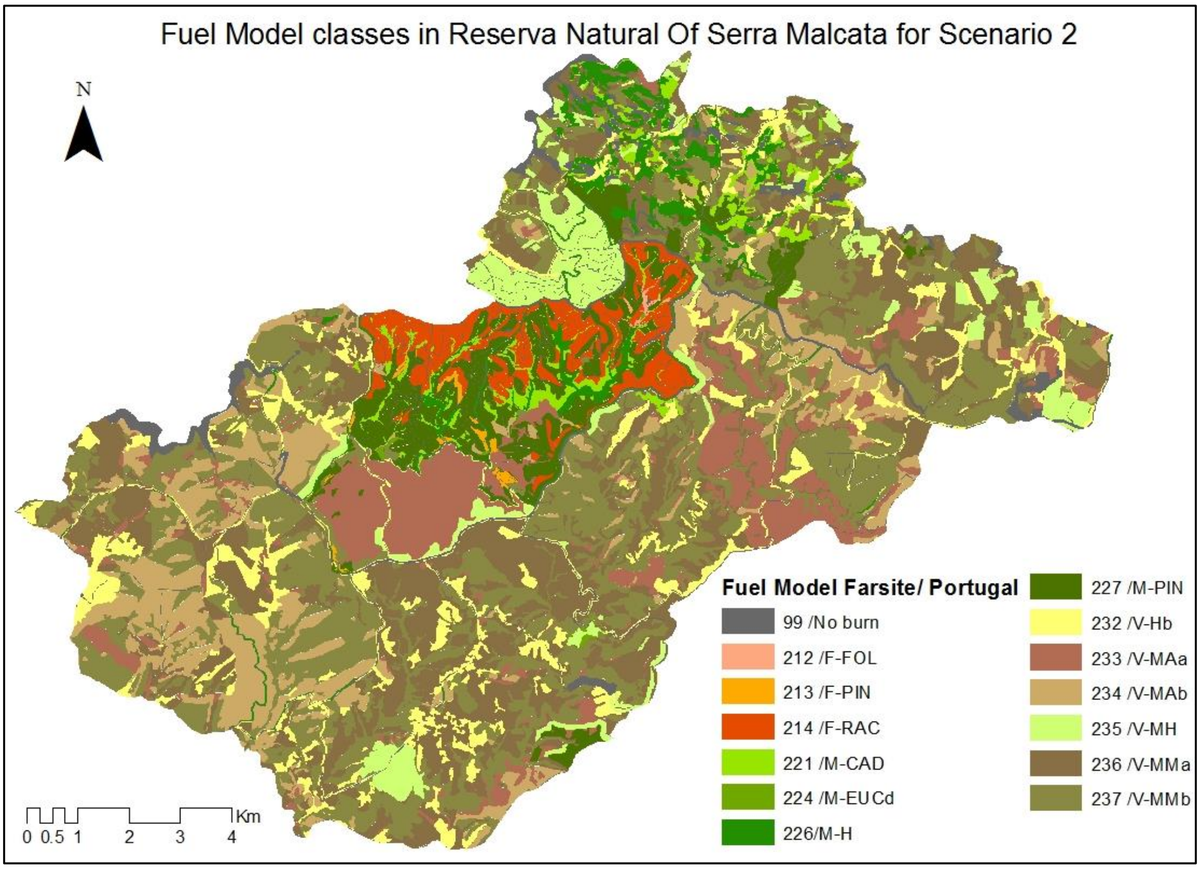

Fig 16. Fuel model types of RNSM according to Farsite number and its correspondent Portuguese custom fuel model for Scenario 1.

The fuel treatments done for the scenario 2 resulted in fuel models with low fuel loads represented by 226 for woodlands and 232 for shrublands. Table 10 contains the relationships of fuel models between the Scenario 0 and Scenario 2. Forestry road and fuel break network kept the same fuel model class because of their maintenance.

Table 10. Fuel treatments done and the canopy cover changes relationships between target land cover classes of the Scenario 0 and Scenario 1.

Fuel treatments		Fuel model Scenario 0	Fuel model Scenario 2
Forestry road network & Fuel breaks network		99/ No burn	99/ No burn
Buffer 15m each side	Maritime pine	234, 227, 235 or 213/ V-MAb, M-PIN, V-MH or F-PIN	226/ M-H
	Black pine	234, 227, 235 or 214/ V-MAb, M-PIN, V-MH or F-RAC	
	Douglas-fir	234, 214/ V-MAb or F-RAC	
	Pyrenean oak	221/ M-CAD	226/ M-H
	Holm oak	237/ V-MMb	
	Chestnut	221/ M-CAD	
	Strawberry tree	237/ V-MMb	
	Eucalyptus	237, 233, 235 or 224/ V-MMb, V-MAa, V-MH or M-EUCd	224/ M-EUCd
	Mediterranean shrub	237, 236, 234 or 233/ V-MMb, V-MMa, V-MAb or V-MAa	232/ V-Hb
Treatments done within Natura 2000	Habitat 9230 (Galaico-portuguese oak-woods with *Q. pyrenaica* dominance)	221, 234 or 233/ M-CAD, V-MAb or V-MAa	226/ M-H
	Habitat 5330 (Thermo-Mediterranean and pre-steppe scrub)	237/ V-MMb	
	Habitat 9340 (*Q. ilex* & *A. unedo* forests)	221 or 236/ M-CAD or V-MMa	
	Habitat 4030 (European Dry Heaths)	236 or 233/ V-MMa or V-MAa	232/ V-Hb

Canopy cover

As well as in the Scenario 1, fuel treatments have produced changes in the canopy cover of the treated areas (Figure 17). As shows the table 11, fuel treatments that affected to the canopy cover such as thinning were only applied to conifers when it was applied the buffer around the forestry road and fuel break networks. In case of the areas that belong to one Natura 2000 habitat type, fuel treatments did not affect the canopy cover neither treatments applied to buffer zone nor treatments applied explicitly within Natura 2000 ecosystems.

Table 11. Fuel treatments done and the canopy cover changes relationships between target land cover classes of the Scenario 0 and Scenario 2.

<table>
<tr><th colspan="2">Fuel treatments</th><th>Canopy cover Scenario 0</th><th>Canopy cover Scenario 2</th></tr>
<tr><td colspan="2">Forestry road network & Fuel breaks network</td><td>0%</td><td>0%</td></tr>
<tr><td rowspan="9">Buffer 15m each side</td><td>Maritime pine</td><td>44%</td><td rowspan="3">15%</td></tr>
<tr><td>Black pine</td><td>60%</td></tr>
<tr><td>Douglas-fir</td><td>85%</td></tr>
<tr><td>Pyrenean oak</td><td>50%</td><td rowspan="5">Maintain same canopy cover</td></tr>
<tr><td>Holm oak</td><td>30%</td></tr>
<tr><td>Chestnut</td><td>50%</td></tr>
<tr><td>Strawberry tree</td><td>30%</td></tr>
<tr><td>Eucalyptus</td><td>84%</td></tr>
<tr><td>Mediterranean shrub</td><td>0%</td><td>0%</td></tr>
<tr><td rowspan="4">Treatments done within Natura 2000</td><td>Habitat 9230 (Galaico-portuguese oak-woods with Q. pyrenaica dominance)</td><td>50%</td><td rowspan="3">Maintain same canopy cover</td></tr>
<tr><td>Habitat 5330 (Thermo-Mediterranean and pre-steppe scrub)</td><td>30%</td></tr>
<tr><td>Habitat 9340 (Q. ilex & A. unedo forests)</td><td>30%</td></tr>
<tr><td>Habitat 4030 (European Dry Heaths)</td><td>0%</td><td>0%</td></tr>
</table>

Regarding to the distribution of the different canopy cover classes (Table 12), 0% and 20% continued being the classes with more extension within RNSM with the 44.27% and 25.24%, respectively. In comparison with Scenario 0 and 1; the percentages of both classes continued being really similar. Canopy classes 10%, 84% and 15% were the ones with less extent (Figure 17).

Table 12. Canopy cover classes and their extension in Scenario 2 of the preserved area of Serra Malcata.

Canopy cover (%)	Percentage occupied
0	44.27%
10	0.16%
15	0.51%
20	25.24%
30	4.38%
44	8.03%
45	2.04%
50	4.36%
60	6.64%
84	0.80%
85	**3.54%**

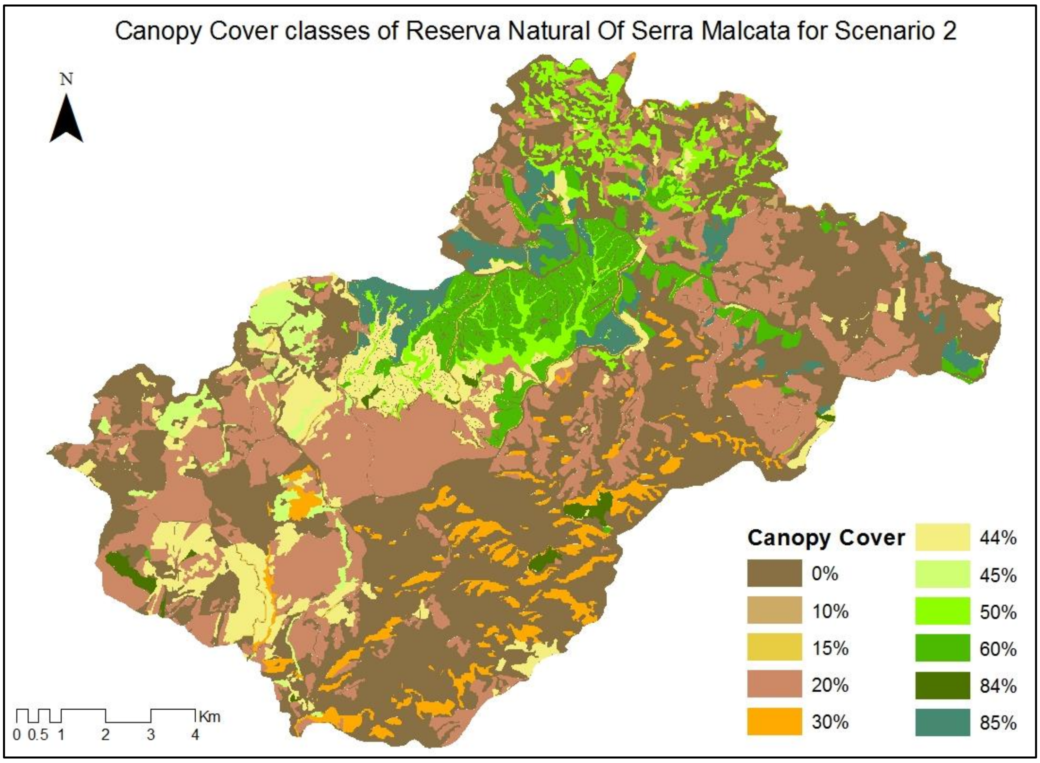

Fig 17. Canopy cover classes for Scenario 2 in RNSM.

4.2.1.4. Buffer area

Besides to the study area, it was construct a buffer area of 4 km surrounding RNSM. The purpose of this buffer was the same as the one describe by Ager et al. (2012), to avoid edge effect and capture the possible impacts of wildfires located outside the area that could spread inside of the area where the fuel treatments changed.

The process for constructing the buffer zone was similar to the one followed to build the all the Scenarios. It was used the land cover classification described by the COS2007 of the buffer together with georeferenced information of the buffer area took from the fuel model *layer* that cover the whole Portugal (Instituto da Conservação da Natureza e das Florestas (ICNF) 2015). After it was classified in CLC classes and reclassified into fuel models and canopy cover classes. Once buffer of 4 km was created, it was merged with the Scenarios 0, 1 and 2 in order to generate the different landscape files for doing the simulations (Figure 18). Elevation, aspect and slope *layers* were created too.

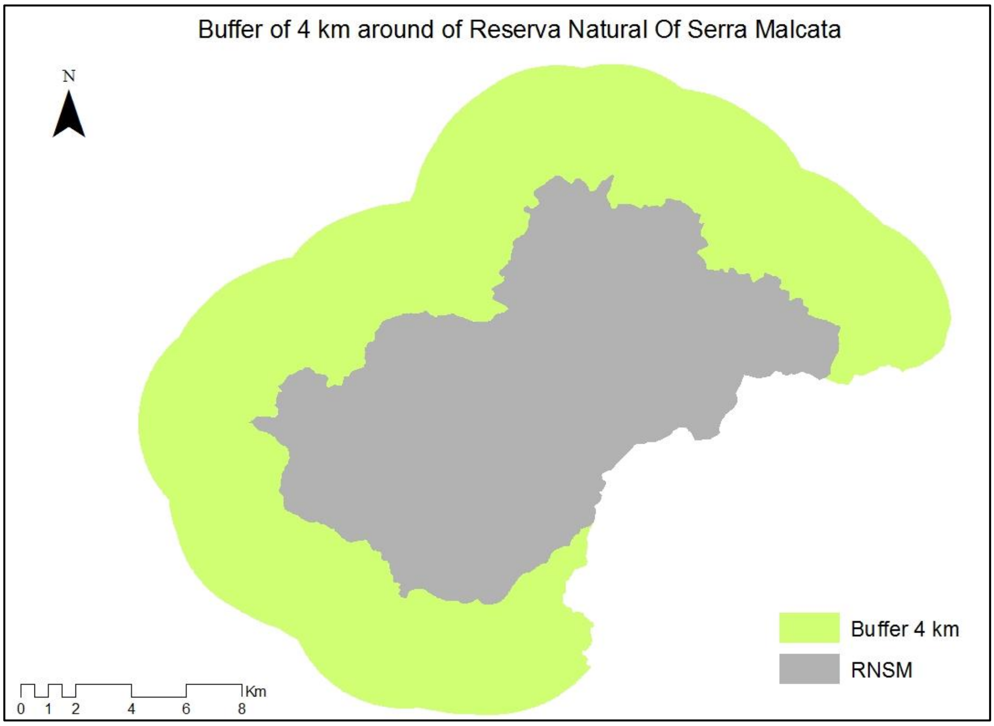

Fig 18. Buffer of 4 km around of Reserva Natural of Serra Malcata.

4.2.2. Weather scenarios

The weather scenario input contains important information related to the speed, direction and their associated duration and probability within a file with .txt format. In our case, the effects of topography on wind direction were not taken into account assuming constant wind speed and direction. However, there is a difference among RANDIG and FlamMap in terms of the number of constant wind direction that can be used for simulation simultaneously. Meanwhile

FlamMap considers only one constant wind direction; RANDIG can consider different constant wind directions with different probabilities. In that way, RANDIG increases the reality of their simulations by increasing the quantity of different wind directions that occurs at different probabilities.

Wind direction and speed were obtained from a 0.04º grid resolution (~5km) after a meteorological re-analysis (Prof. Carlos da Camara personal observation) since real meteorological data of the area were not available. The database contained average daily data of the U and V wind components in m/s measured at 10m for a time-series of 36 years (1979 to 2015). U and V horizontal wind components are the mathematical representation of both wind speed and direction and they represent west-east and south-north directions respectively (Harrison, 2014).

From the database, it was constructed the extreme weather scenario. The data analysis was limited for the data above the percentile 95 of the distribution of wind speed registered during the months in which wildfires are more likely to occur in Portugal due to weather conditions (Pereira et al., 2005), that is June, July, August and September. However, it is necessary to point that the data used, although showing extreme conditions, could omit extreme meteorological information since each data record corresponds with average daily wind speeds.

As well as in other fire simulators such as FlamMap or FARSITE, RANDIG needed the wind input parameters expressed in miles per hour (mph) measured at 20ft (~6m), since the fire simulator adjust automatically the input wind information into midflame winds based on the surface fuel depth and overstory values of each pixel (Andrews, 2012).For that reason, both wind component were converted from m/s into miles per hour (mph) by multiplying by conversion factor (1m/s is ~2.24 mph).

Firstly, wind speed was determined by using Pythagorean Theorem.

$$Wind\ speed = \sqrt{(u^2 + v^2)} \qquad \text{Eq. 5}$$

After that, they were transformed from measures took at 10 m into 6 m by dividing by the conversion coefficient which is 1.15 which assumes that there is enough clear surface for not vary wind speed (Turner and Lawson, 1978).

Secondly, it was determined wind direction using trigonometry again. Wind distribution was expressed in azimuthal degrees. For this aim, it was used:

$$Wind\ direction = \mathrm{Tan}^{-1}(v/u) \qquad \text{Eq. 6}$$

However, it was done carefully paying attention to the quadrant in which the angle is returned *i.e.* U and V components in the fourth quadrant (Harrison, 2014). Both wind direction distributions obtained did not clearly shown which were the most common wind distribution in the study area for medium and extreme weather scenarios, so the wind direction distributions were reclassify from the 360º into 8 classes which represented the azimuthal degrees for the eight main azimuthal degrees: North (0º), Northeast (45º), East (90º), Southeast (135º), South (180º), Southwest (225º), West (270º), Northwest (315º). The most common wind directions were the winds coming from North and South (Figure 19).

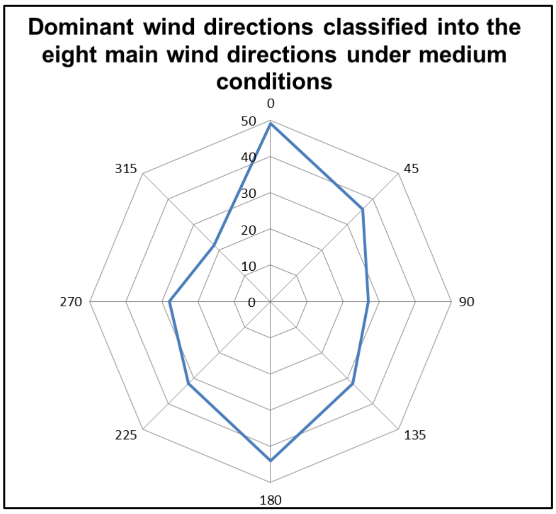

Fig 19. Dominant wind directions within the Reserva Natural of Serra Malcata expressed according to the eight main wind directions under extreme weather conditions.

Once wind direction and speed were estimated, it was determined the most common ones of the area and estimated their probabilities. Wind speeds were ranged in groups of speeds, assuming that differences of 1 or 2 km/h did not make big differences. In addition, this also helped for the accountability of the most repeated wind speed and direction. According to this, it was created 4 groups which ranged wind speed between 0 to 20 mph. Once grouped, it was obtained the wind speed and direction more common in the study area for both weather scenarios.

The most probable wind directions and speeds under extreme weather conditions were North and South winds at 13 mph (≈21 km/h) (Table 13). Related to the duration that appears in the table 13, it refers to the duration in minutes of the burning period that was set after calibrating the fire simulator. The burning period was set at 24h and transformed in minutes, 1440 min. The calibration and validation approach will be explained in other epigraph.

Table 13. Most common wind speed, wind direction of the study area, their duration for the simulation and the probability of occurrence under extreme weather conditions.

Wind speed (mph)	Wind direction (az. Degrees)	Duration (min)	Probability (%)
13	0	1440	0.18
13	45	1440	0.13
13	90	1440	0.10
13	135	1440	0.12
13	180	1440	0.16
13	225	1440	0.12
13	270	1440	0.10
13	315	1440	0.08

4.2.3. Fuel moisture, Fuel model file descriptor file and probability ignition grid

Fuel moisture

Fuel moisture file contains the information related to the quantity of water keep by both dead and living plants. The determination of them is an important factor because it will determine the fuel availability for fire ignition and combustion of the fuels within the study area in the simulation.

Fuel moisture content for 1h, 10h and 100h dead fuel size classes took values of 6%, 7% and 8%, respectively while for live fuels it was assumed 85% for herbaceous and 95% for woody fuels. The selection of these values for fuel moisture content was done in an arbitrary way based in previous studies done. It was assumed same fuel moisture content for all the fuel models used in the three Scenarios. The format of the file was .fms which was converted from a text file.

Fuel model descriptor

Fuel model descriptor file contains the metrics of the custom fuel models that are used in the simulation and their relationships with the fuel models used by FlamMap in the fire simulations. In this case, it contains the metrics such as the fuel load for the different fuel size classes for the total eighteen set of custom fuel models described for Portugal (Fernandes et al., 2009). The format of the file was transformed in .fmd extension from a text file with the information.

Ignition probability grid

RANDIG can generate ignitions located randomly or located according to an ignition probability grid. In a first approach, it was used the ignition probability grid developed for the continental Portugal (Catry et al., 2009). For this aim, from the ignition risk raster layer with a spatial resolution of 250x250m was taken the ignition probability grid of RNSM and converted to a spatial resolution of 90x90m, the one decided for simulations. However, once the simulation was running, the system did not recognize the ignition probability grid. Therefore, at the end, it was decided to run RANDIG with randomly location of ignitions.

4.3. Fire simulation validation

Once the seven inputs (it was not used the ignition probability grid) needed where obtained, the simulations were done. For executing the simulations in RANDIG, it was needed to create a file which contains the rules that RANDIG will follow for creating the simulations. The file contained thirteen arguments: LCP file, FMS file, FMD file, Weather scenario file, Number of scenarios, Resolution, number of ignitions, Number of threads, Output file name, Ignition probability grid, Distance units, Crown fire calculation method and WindNinja resolution. After that, the simulations must be calibrated and validated by using the historical distribution of the fires in the area.

4.3.1. Historical fire distribution in Reserva Natural of Serra Malcata

All simulations should be validated with real data to calibrate the simulation, because if not the results obtained from the simulation would not be close to the reality. In case of fire simulations for burn probabilities calculation, the validation is done with data that explains the historical distribution of burned area and number of ignitions related to fire size classes.

Ideally, the data used should be only related to the wildfires occurred inside of RNSM but the number of fires registered within the study area were almost inexistent. For that reason, the data used, taken from the official databases of forest fires of Portugal done by the ICNF (Instituto da Conservação da Natureza e das Florestas (ICNF), 2015b), was extracted the for Sabugal and Penamacor municipalities where the preserved area is located. However, as the study area represented a relatively small surface if compared with the total area of both municipalities, it was decided to limit the dataset at parish level in order to obtain a more adjust historical fire distribution. Finally, the dataset, of a 34 years (1980-2014) time series, was built using the number of ignitions and burned area data from the parish of Malcata, Quadrazais, Vale de Espinho and Foios that belongs to Sabugal municipality and from Penamacor, Meimoa and Meimão belonging to Penamacor municipality.

The data was treated in order to obtain the historical distribution of number of ignitions (in percentages) of each fire size class (Fig. 20A) and burned area (in percentages) related to fire size class (Fig. 20B). The fire size classes chosen for representing both distributions were fire size <50 ha, 50-100 ha, 100-200 ha, 200-500 ha, 500-800 ha, 800-1500 ha, 1500-2500 ha and >2500 ha. Both graphs shown the typical phenomenon that happens in Portugal, as elsewhere in Mediterranean Basin, where the big majority of the ignitions produce small wildfires but few of them account for the majority of the burnt area (Pereira et al., 2006). However, regarding to the burnt area, although the major part of it is normally produced by large forest fires, it is case and contrary to the normality, there was a big proportion of burned area produce by smaller size fires (in this case <50 ha).

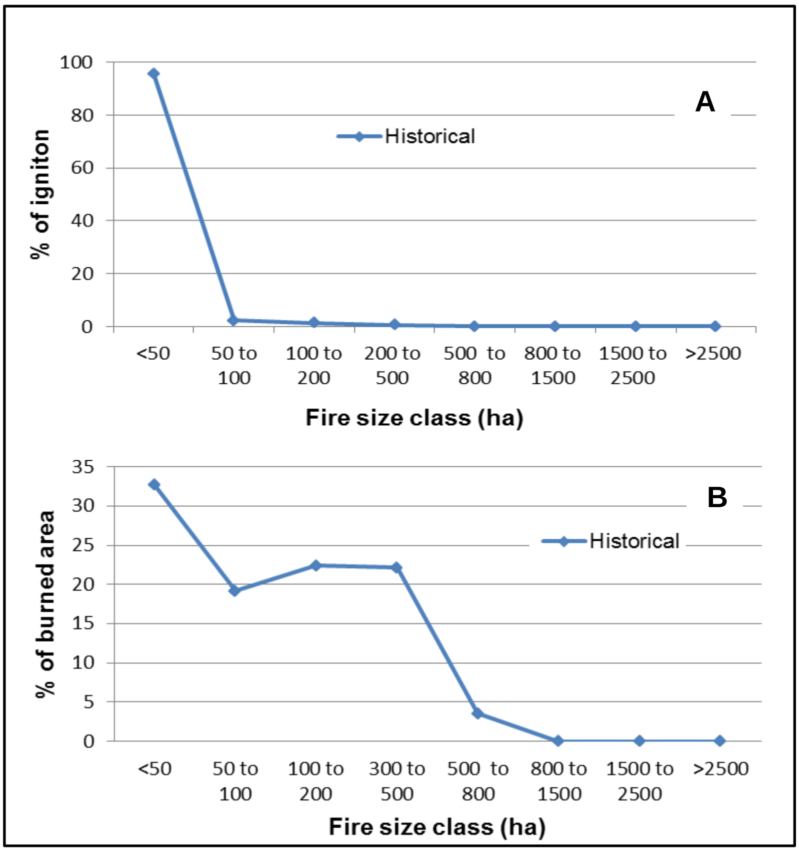

Fig 20. Historical fire distribution of Reserva Natural de Serra Malcata. Figure 20A corresponds to the distribution in percentages of number of ignitions related to fire size classes. Figure 20B corresponds to the distribution of burned area in percentages related to fire size classes.

4.3.2. Simulation validation: Burn period time

The simulation framework set must be calibrated to make possible to generate simulations that are the most close to the reality in order to achieve the best plausible results. For that reason, it was compared the historical fire distributions of ignition and burnt area by fire classes in RNSM with a set of simulations of the Scenario 0 (current reality) in which were selected different burn period times: 6h, 12h, 18h, 24h. Then, the simulation distribution for a burn period that is in good agreement with the historical distribution was the selected burn period to be used.

As previously commented, simulations were done including a buffer area of 4 km around the study area with the aim to include possible effects of wildfires generated outside of RNSM. However, to choose the most suitable burn period it was used only the information related to the study area, so it was extracted from the outputs generated.

Comparisons between the historical fire distribution and the simulated fire distributions gave contradictory results. All burned periods were really different from the historical data, i.e. comparison historical data with 12h and 24h (Figure 21). Analyzing more in detail the historical data, it was possible to observe that the majority of the wildfires registered were smaller than 1 ha. This indicated suppression activities were successful and few wildfire escapes, resulting in a few events >50 ha to compare with simulations distributions.

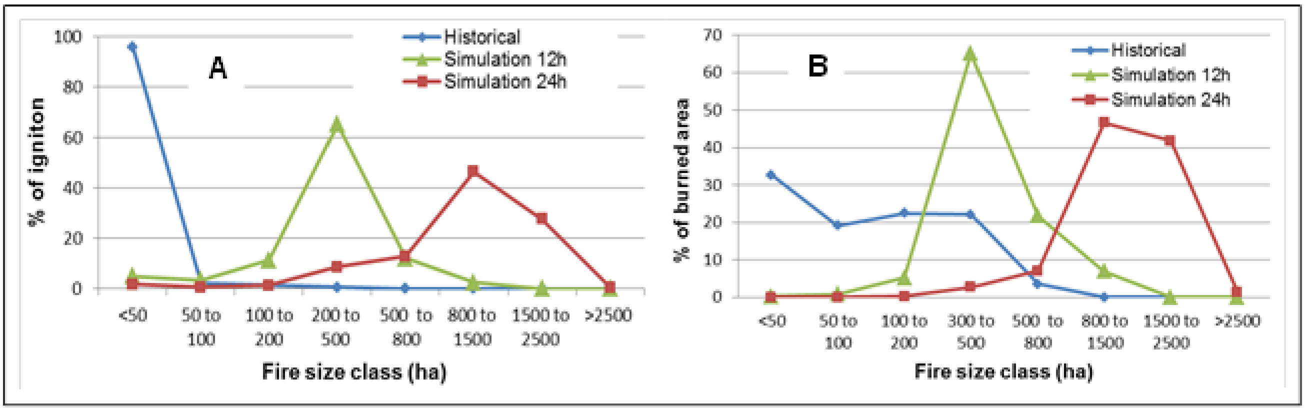

Fig 21. Comparison of historical fire distribution with simulations with burn periods 12h and 24h. Figure 21A corresponds to the distribution in percentages of number of ignitions related to fire size classes. Figure 21B corresponds to the distribution of burned area in percentages related to fire size classes.

This fact represented an important issue for validating the simulation. For that reason, in a first step, it was analyzed the largest wildfires registered in the area having special attention to the burned area and their duration. In a second step, they were compared with the mean burned area of the different burn periods. Comparisons showed that if it is assumed that wildfires can be extrapolated for matching with the duration of the different burn periods and compared with the mean burned area of these; the most suitable burn period is 24h. So according to this fact, it was assumed 24h as the most appropriate burned period for doing simulations since it was the most closest to the historical data..

5. RESULTS

After setting 24h as the burning period, 50 000 ignitions were simulated within the three scenarios and different weather scenarios for obtaining the maps of burn probability (BP), conditional flame length (CFL) and the fire size perimeters. It was simulated 50 000 ignitions since the outputs obtained after the simulations were strong enough for doing an appropriated fire exposure assessment.

5.1. Fire size distributions

In general terms, the contribution of the different fuel size classes to the total number of ignition and the total burned area was similar for the three Scenarios. The three scenarios distributions followed a quasi-normal distribution. Simulated wildfires between 1201 and 1600 ha were the fire size class that accounted for more number of ignitions and burned area with the 27-30% and 34-36% respectively depending on the scenario (Figure 22).

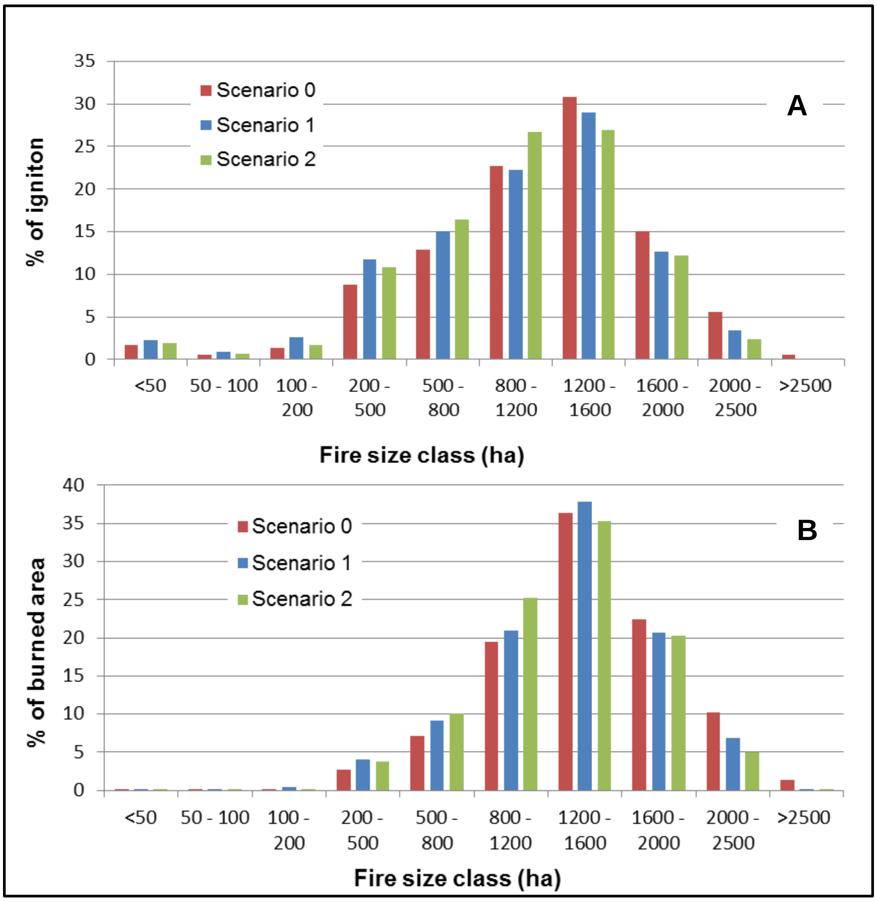

Fig 22. Effects of fuel treatments represented by three scenarios on the distribution in percentages of number of ignitions(A) and fire size classes (B) related to fire size classes.

Differences between the three scenarios were observed. As presumed, Scenario 0 (Sc0), base-line scenario, had higher percentages in the largest fire size classes and lower percentages in the smaller fire size classes than Scenarios 1 (Sc1) and Scenario 2 (Sc2)

(Table 14). The largest differences both negative as positive between Sc0 and treated scenarios were founded the biggest fire classes.

Table 14. Wildfire simulation summary. Fire size class (ha), baseline Scenario (Sc0) and treated Scenarios (Sc1 &Sc2), percentages of ignitions and burned area (BA) by fire class and the differences between baseline's Scenario and treated and fire statistics (median, mean and standard deviation (SD)).

Fire size class (ha)	Treat.	Ignitions (%)	Δ Ignitions (%)	BA (%)	Δ BA (%)	Median	Mean	SD
<50	Sc0	1.6		0.03		17	20	11.2
	Sc1	2.3	-0.6	0.04	-0.01	18	20	12.3
	Sc2	1.8	-0.2	0.04	-0.01	17	20	11.7
51 to 100	Sc0	0.5		0.03		73.5	74	14.6
	Sc1	0.9	-0.4	0.06	-0.03	72	74	14.6
	Sc2	0.6	-0.09	0.04	-0.01	71	72	14.9
101 to 200	Sc0	1.3		0.17		153	152	28.5
	Sc1	2.6	-1.3	0.37	-0.2	151.5	151	27.2
	Sc2	1.7	-0.4	0.09	0.08	154	154	27.7
201 to 500	Sc0	8.7		2.72		375	368	82.9
	Sc1	11.7	-3	4	-1.28	370	366	83.2
	Sc2	10.9	-2.1	3.77	-1.05	377	370	83.2
501 to 800	Sc0	12.8		7.11		659	656	86.9
	Sc1	15.1	-2.3	9.19	-2.08	653	652	85.2
	Sc2	16.5	-3.6	10.15	-3.04	662	657	86.1
801 to 1200	Sc0	22.7		19.51		1023	1016	115.2
	Sc1	22.3	0.4	20.89	-1.38	1007	1006	114.3
	Sc2	26.7	-4	25.2	-5.69	1010	1005	114
1201 to 1600	Sc0	30.8		36.41		1396.5	1399	111.8
	Sc1	29	1.8	37.85	-1.44	1394	1354	83.8
	Sc2	27	3.8	35.33	1.08	1355	1396	114.1
1601 to 2000	Sc0	15		22.4		1739	1761	115.9
	Sc1	12.6	2.4	20.68	1.72	1647	1682.8	135.7
	Sc2	12	3	20.26	2.14	1748	1766	113.3
2001 to 2500	Sc0	5.6		10.27		2142	2174	134.7
	Sc1	3.4	2.2	6.81	3.46	2145.5	2170	125.4
	Sc2	2.4	3.2	4.93	5.34	2118	2151	116.2
>2501	Sc0	0.6		1.36		2613	2638.6	109.3
	Sc1	0.04	0.56	0.11	1.25	2528	2533	27.7
	Sc2	0.08	0.52	0.2	1.16	2659	2653	73.9

Both Sc1 and Sc2 had more representativeness on smaller fire classes (classes going from <50 until 1200 ha) than Sc0 related to both the total number of ignitions and burned area (Table 14). These differences were slightly smaller for fire size classes until 100 ha and smaller for fire class 101 to 200 ha ranging between centesimal until the 1%. Larger differences were found for fire classes until 1200 ha in which Sc1 and Sc2 had more representativeness than Sc0 with differences between 1 to 4%. However, the opposite tendency was found for the largest fire size classes where Sc0 had more weight than treated Scenarios on the total percentage of number of ignitions and burned area. Differences ranged between 1 until 6%.

The largest differences between scenarios regarding to the percentage of the total number of ignitions were reported for fire size classes among 501-800 ha until 2001-2500 ha. Fire size classes within 501 until 1200 ha had bigger percentages in the Sc0 than in treated ones; the differences were between 2.1 to 4%. On the other hand, larger fire size classes within 1201 to 2500 ha had bigger percentages of number of ignitions in Sc1 and Sc2 than baseline Scenario; in this case, percentages varied between 1.8 and 3.2% (Table 14).

Related to the total percentage of burned area, the largest differences were founded between Sc0 and Sc2. These differences had different signs. For fire size class 801 to 1200 ha, Sc2 had bigger weight on the total simulated burned area than Sc0 with a difference of 6%. Contrary, a similar difference was found for 2001 to 2500 ha fire class; in this case, Sc0 was a 5.34% and 3.46% more representativeness of the total burned area than Sc2 and Sc1, respectively (Table 14).

Comparing Sc1 and Sc2 fire size class distribution related to ignitions, Sc1 registered higher percentages for fire size classes equal or larger than 1200 to 1600 ha than Sc2 whereas Sc2 presented higher percentages in fire size classes smaller than 1200 ha (Figure 22A). This showed that treatments done in the Sc2 shifted the distribution towards the y-axis, producing the increase in the representativeness of smaller fire size classes over the total number ignitions.

Regarding to the effect of the different treatments on the burned area distribution by fire classes (Figure 22B), the pattern followed by the Sc1 and Sc2 was the same as before, larger fire size classes (more than 1200 ha) accounted for more percentage of the burned area in Sc1 than the same fire size classes of Sc2, while for smaller fire size classes are more representative in Sc2 than in Sc1.

5.2. Burn probability and conditional flame length in Reserva Natural of Serra Malcata

Fire exposure was assessed for RNSM by using BP and CFL simulation outputs. Comparisons were done between different fuel treatments (Sc0, Sc1 and Sc2) under extreme weather conditions.

5.2.1. Burn probability within RNSM

Burn probability ranged from 0.0 to 0.0583 with an average of 0.0334 for the baseline scenario Sc0 which means that, on average, each pixel was burned 1670 times. Scenarios Sc1 and Sc2, where fuel treatments were done attending to different criteria, had an average burn probability of 0.0279 and 0.0277, respectively. BP differences of Sc1 and Sc2 related to Sc0 were similar. BP decreased 16.50 and 16.93% related to Sc0 respectively (Table 15). However, if maximum BPs were observed, it is seen bigger differences between Sc2 and Sc1.

Table 15. General burn probabilities statistics of simulated scenarios (Sc0, Sc1 and Sc2) and differences at pixel-level between scenarios. Differences: Increase (+), decrease (-).

Treat.	Mean	ΔBP	Diff. (%)	SD	BP Max
Sc0	0.0334			0.0119	0.0583
Sc1	0.0279	0.0055	-16.50	0.0118	0.0533
Sc2	0.0277	0.0057	-16.93	0.0106	0.0514

For a detailed analysis, burn probabilities were classified into 6 different classes (Table 16). The criteria followed for defining the class groups was based on the quantile distribution of Sc0. Both small increase and decrease of BP values between Scenarios were registered for the majority of the BP classes. Bigger differences were observed for both extreme BP classes (0 to 0.022 and 0.044 to 0.583), where treated scenarios had smaller BP than baseline scenario. The exception of this tendency was observed between Sc0 and Sc2 for 0 to 0.022 BP class were Sc2 had an increase on the average burn probability.

Table 16. Average burn probabilities of simulated scenarios (Sc0, Sc1 and Sc2) per BP classes and differences (ΔBP= Sc0-Sc1 or Sc0-Sc2) at pixel-level between scenarios by burn probability class. Differences in percentage: decrease (-) and increase (+).

BP class		Sc0	Sc1	Sc2
0-0.022	**Mean**	0.0135	0.0122	0.0143
	ΔBP		0.0012	-0.0008
	Diff. (%)		-9.1	+6.3
0.022-0.029	**Mean**	0.0260	0.0263	0.0262
	ΔBP		-0.0003	-0.0002
	Diff. (%)		+1.3	+0.8
0.029-0.036	**Mean**	0.0335	0.0333	0.0325
	ΔBP		0.0001	0.0010
	Diff. (%)		-0.4	-2.9
0.036-0.04	**Mean**	0.0380	0.0377	0.0378
	ΔBP		0.0003	0.0002
	Diff. (%)		-0.8	-0.6
0.04-0.044	**Mean**	0.0416	0.0417	0.0418
	ΔBP		-0.00001	-0.0001
	Diff. (%)		+0.01	+0.3
0.044-0.0583	**Mean**	0.0492	0.0463	0.0470
	ΔBP		0.0029	0.0022
	Diff. (%)		-5.8	-4.5

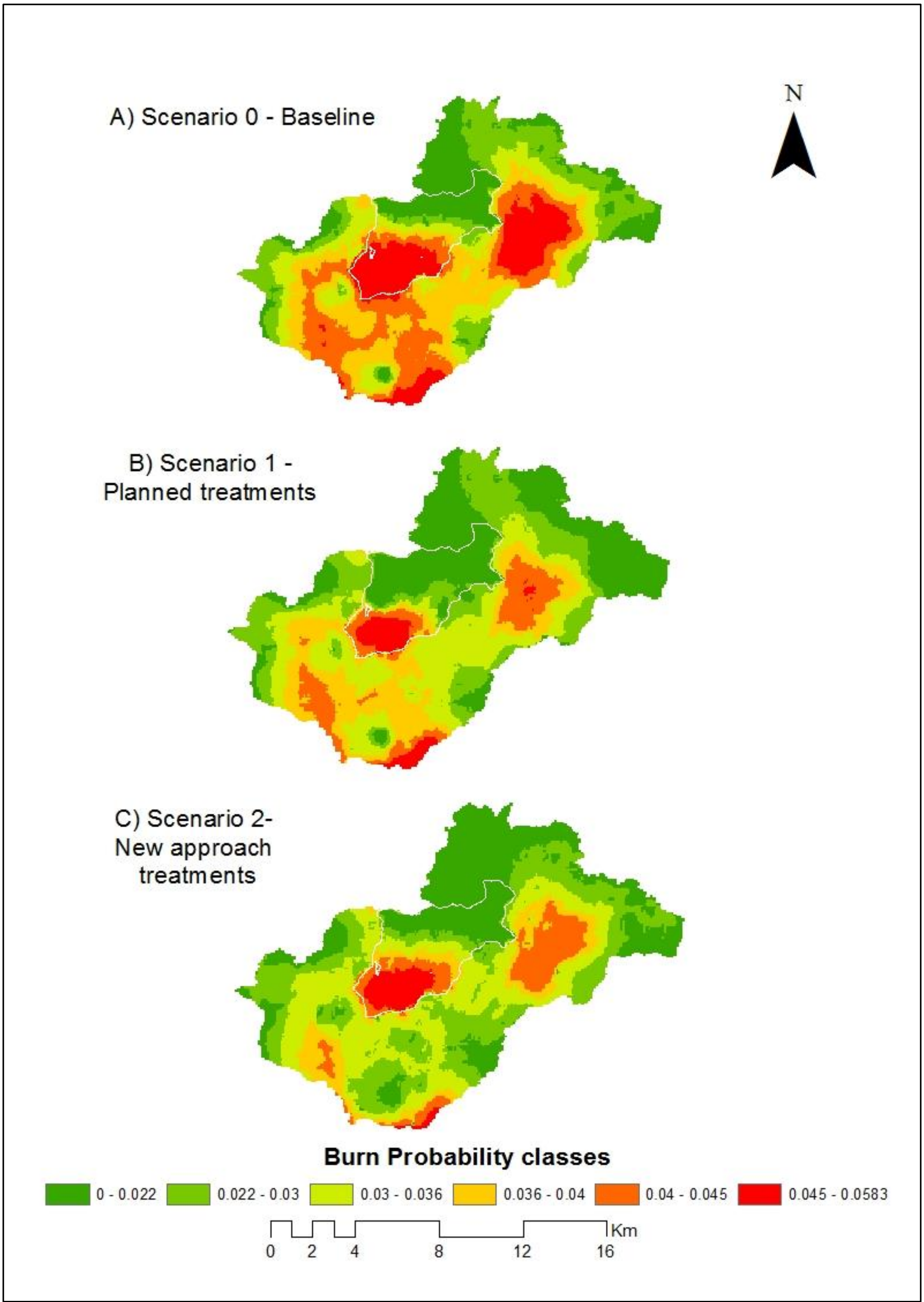

Fig 23. Effects of fuel treatments over Scenario 0 (A) and fuel managed Scenario 1 (B) and Scenario 2 (C) on burn probability classes within Reserva Natural of Serra of Malcata (gPS area located within the preserved area).

Changes between the extensions occupied by the different BP classes were visible too (Figure 23). The extension occupied by high BP classes in Sc0 decreased both in Sc1 and

Sc2, whereas the extension of the smallest BP classes followed the opposite tendency, they increased both Sc1 and Sc2 respected to Sc0 (Table 17).

Surfaces belonging to high BP class were associated to dense Mediterranean shrub meanwhile a big proportion of the area within small BP classes corresponded to gPS area, which is more actively managed. In fact, it was possible to observe differences between the extensions occupied by the different BP classes in Sc1, more focused on protection measurements for production goals and Sc2 which is more focused in conservation purpose respected Sc0 (Fig. 23)

In general terms, the extension occupied by the different BP classes presented more differences in Sc2 than in Sc1 respected Sc0, in fact, Sc2 experienced a higher surface exchanged than Sc1. However, there were cases in which Sc1 registered more variability respected to Sc0 such as in 0-0.022 or 0.04 to 0.044 classes. The highest BP class showed less extension in Sc2 than in Sc1 respected Sc0 while the lowest BP class had more extension in Sc1 than in Sc2 if compare with Sc0. BP classes 0.0022 to 0 0.029 and 0.036 to 0.04 registered the maximum difference among Sc1 and Sc2 respected to Sc0 (Table 17).

Table 17. Surface (ha) of simulated scenarios (Sc0, Sc1 and Sc2) by BP classes and differences (ΔSurface= Sc0-Sc1 or Sc0-Sc2) at pixel-level between scenarios by burn probability class. Differences in surfaces presented in percentages negative (-) and positive (+).

BP class		Sc0	Sc1	Sc2
0-0.022	**Surface (ha)**	2700.5	4598.4	4348.1
	ΔSurface (ha)		-1897.83	-1647.54
	Diff. (%)		+70.3	+61.0
0.022-0.029	**Surface (ha)**	2847.2	3299.9	4293.8
	ΔSurface (ha)		-452.79	-1446.6
	Diff. (%)		+15.9	+50.8
0.029-0.036	**Surface (ha)**	2399.2	3623.9	4154.5
	ΔSurface (ha)		-1224.72	-1755.3
	Diff. (%)		+51.0	+73.2
0.036-0.04	**Surface (ha)**	3258.6	2624.4	1409.4
	ΔSurface (ha)		634.23	1849.23
	Diff. (%)		-19.5	-56.7
0.04-0.044	**Surface (ha)**	2501.3	1233.6	1292.0
	ΔSurface		1267.65	1209.33
	Diff. (%)		-50.7	-48.3
0.044-0.0583	**Surface (ha)**	2462.4	788.9	671.5
	ΔSurface (ha)		1673.46	1790.91
	Diff. (%)		-68.0	-72.7

5.2.2. Conditional flame length within RNSM

Conditional flame length (CFL) ranged from 0 to 3.69 m for the Sc0 with an average flame length value of 1.55 m. Scenarios 1 and 2 had average flame lengths of 1.42 and 1.43 m with maximum CFL of 3.68 and 3.72 m. On percentages, the decrease of Sc1 and Sc2 respected to Sc0 were 8.23 and 7.76%, respectively (Table 18). Differences between treatments were tiny.

Table 18. Conditional Flame Length statistics of simulated scenarios (Sc0, Sc1 and Sc2) and differences at pixel-level between scenarios. Differences: Increase (+), decrease (-).

Treat.	Mean	ΔCFL	Diff. (%)	SD	CFL Max
Sc0	1.55			0.788	3.69
Sc1	1.42	0.127	-8.23	0.792	3.68
Sc2	1.43	0.120	-7.76	0.807	3.72

For a deeper analysis, CFL was subdivided in classes of CFL attending to the relationships between fire flame length and suppression capabilities interpretation. According to this, it was classified CFL into the classes 0-1.2, 1.2-2.4, 2.4-3.4 and higher than 3.4 m. For all classes of Sc1 and Sc2, the average CFL decreased respect to Sc0. The unique exception was presented by flame lengths between 2.4 to 3.4 m class in the Sc1 where there was an increase of the average CFL (Table 19).

In general, although there was a generalized flame length decrease for all classes, the percentage of decrease was low for small CFL classes and even lower or almost insignificant for large flame lengths.

Table 19. Average Conditional Flame Length of simulated scenarios (Sc0, Sc1 and Sc2) per CFL classes and differences (ΔCFL= Sc0-Sc1 or Sc0-Sc2) at pixel-level between scenarios by burn probability class. Differences in percentage: decrease (-) and increase (+).

CFL (m)		Sc0	Sc1	Sc2
0-1.2	**Mean**	0.84	0.80	0.81
	ΔCFL		0.043	0.032
	Diff. (%)		- 5.1	-3.8
1.2-2.4	**Mean**	1.64	1.60	1.64
	ΔCFL		0.039	-0.003
	Diff. (%)		- 2.4	-0.2
2.4-3.4	**Mean**	3.02	3.03	3.02
	ΔCFL		-0.0087	0.0002
	Diff. (%)		+0.29	-0.01
>3.4	**Mean**	3.51	3.50	3.51
	ΔCFL		0.011	0.002
	Diff. (%)		-0.316	-0.053

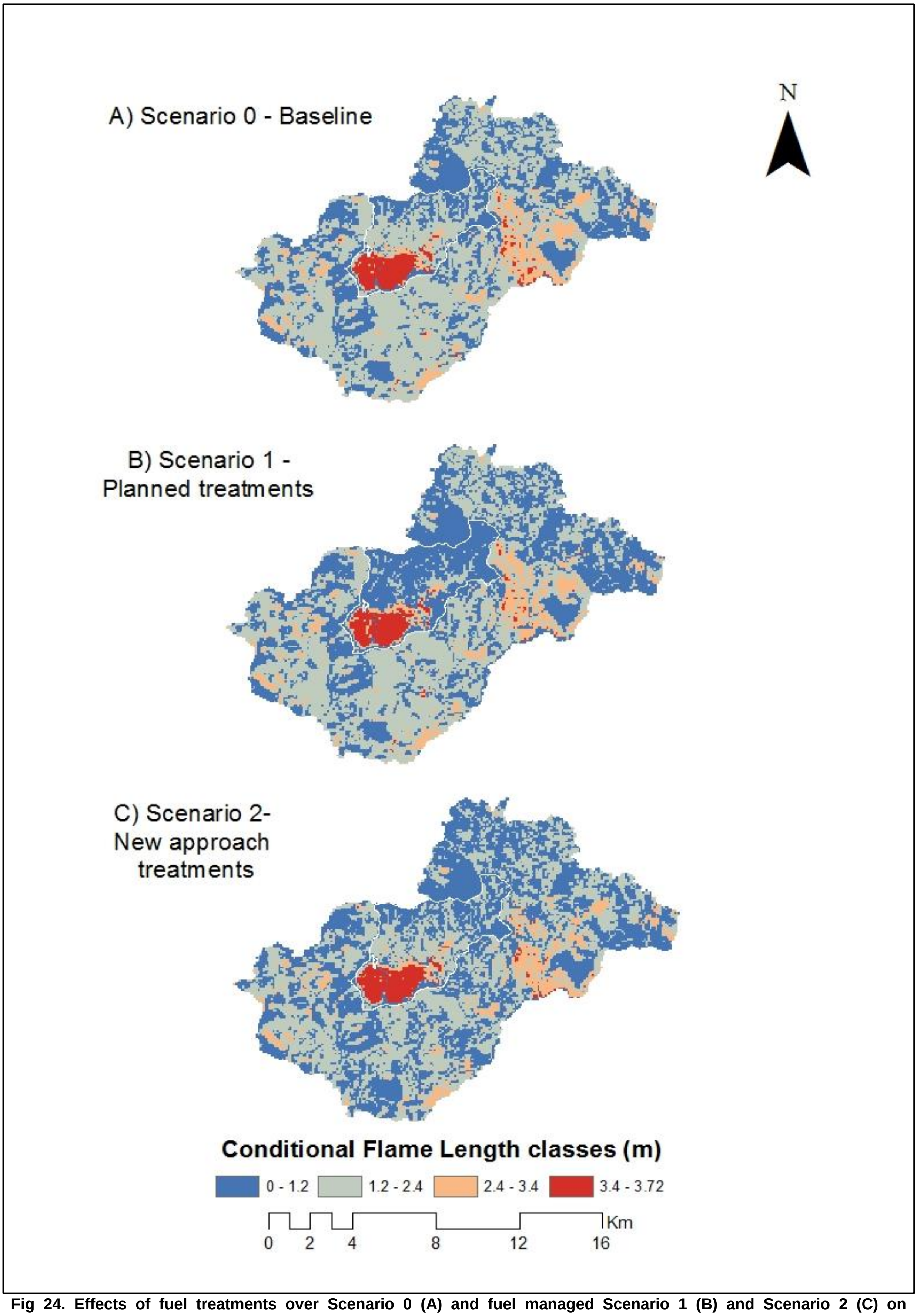

Fig 24. Effects of fuel treatments over Scenario 0 (A) and fuel managed Scenario 1 (B) and Scenario 2 (C) on conditional flame length probability classes within Reserva Natural of Serra of Malcata (gPS area located within the preserved area).

The area occupied by the different CFL classes above defined changed between baseline scenario and treated scenarios (Figure 22). CFL class until 1.2 m of flame length was the unique class which experienced an increase on its extension over RNSM, this increase was 8.6% and 10.7% for Sc1 and Sc2 scenarios related to Sc0. The rest CFL classes suffered a decrease of the area occupied by them, although in this case, changes were only significant for flame length 1.2 to 2.4 m. CFL classes above 2.4 m suffered a inappreciable decrease of the area occupied by them (Table 20). In general, Sc2 suffered a higher exchanged of surface between CFL classes.

Comparing Sc1 and Sc2, there were not appreciated big differences between them. For CFL classes until 1.2 m, Sc2 presented a bigger increase on extension than Sc1; whereas for flame lengths between 1.2 to 2.4 m, Sc2 suffered a bigger decrease than Sc1. Above these CFL, differences between Sc1 and Sc2 are almost inexistent.

The allocation of the fuel treatments differed between Sc1 and Sc2 due to differences of the objectives to achieve. For that reason, it was possible to observe differences on the localization of the areas where there were more reductions. This was the case of gPS area, where it was possible to appreciate a higher CFL decrease in Sc1 than in Sc2. On the other hand, Sc2 had a higher decreased at the north of RNSM than Sc1 where protected Pyrenean forest are located (Figure 24).

Table 20. Surface (ha) of simulated scenarios (Sc0, Sc1 and Sc2) by CFL classes and differences (ΔSurface= Sc0-Sc1 or Sc0-Sc2) at pixel-level between scenarios by burn probability class. Differences in surfaces presented in percentages negative (-) and positive (+).

CFL (m)		Sc0	Sc1	Sc2
0-1.2	**Surface (ha)**	5647.32	7034.57	7369.38
	ΔSurface (ha)		-1387.2	-1722.1
	Diff. (%)		+24.6	+30.5
1.2-2.4	**Surface (ha)**	8521.2	7368.6	7030.8
	ΔSurface (ha)		1152.6	1490.4
	Diff. (%)		-13.5	-17.5
2.4-3.4	**Surface (ha)**	1453.95	1308.96	1291.95
	ΔSurface (ha)		145.0	162.0
	Diff. (%)		-10.0	-11.1
>3.4	**Surface (ha)**	546.75	457.65	477.09
	ΔSurface (ha)		89.1	69.6
	Diff. (%)		-16.3	-12.7

5.2.3. Burn Probability vs. Conditional Flame Length

The relationship between BP and CFL was compared between Sc0, Sc1 and Sc2 in order to observe differences between scenarios (Figure 25). In general, treatments done within Sc2 produced a bigger shift towards a lower CFL and BP values than treatments done in Sc1 related to Sc0. The Figure 25 showed that treatments done both treated scenarios were more effective for decreasing burn probabilities than conditional flame length.

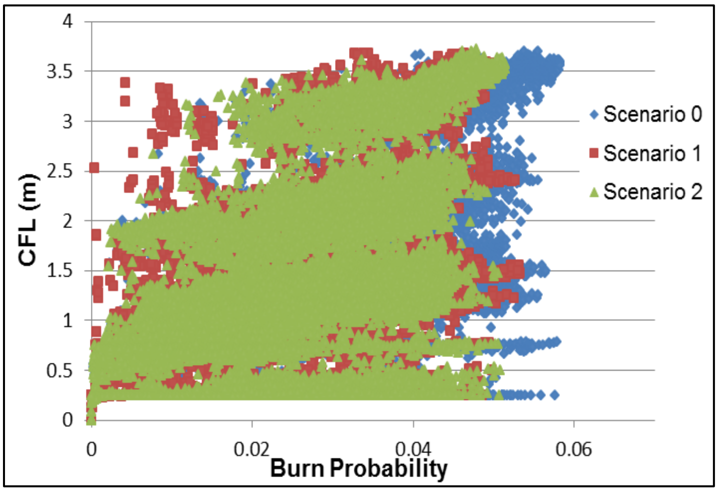

Fig 25. Scatter plots of burn probability *vs.* conditional flame length (CFL) for Scenario 0, Scenario 1 and Scenario 2.

5.3. Burn probability and conditional flame length within Natura 2000 protected ecosystems

Fire exposure of the different ecosystems belonged to the Natura 2000 network was also compared among the three scenarios proposed (Figure 27 and 28). Burn probability in Sc0 ranged between 0 and 0.058 with an average value of 0.037 what meant that on average each pixel burned 1850 times. Both treatments applied on Sc1 and Sc2 produced the BP reduction of the 13% and 19.4% respected to Sc0 (Table 21). In case of the conditional flame length, both treated scenarios decreased their average CFL respected to Sc0 in 4.6% and 13.2% (Table 21).

Table 21. Burn Probability (BP) and Conditional Flame Length (CFL) statistics of simulated scenarios (Sc0, Sc1 and Sc2) and their differences at pixel-level between scenarios within Natura 2000 habitat types3150, 3260, 91E0 and 5330. Differences: Increase (+), decrease (-).

Treat.	Mean BP	ΔBP	Diff. (%)	BP Max	Mean CFL (m)	ΔCFL	Diff. (%)	CFL Max (m)
Sc0	0.037			0.058	1.73			3.70
Sc1	0.033	0.0048	-12.9	0.053	1.65	0.08	-4.6	3.68
Sc2	0.030	0.0073	-19.4	0.051	1.50	0.23	-13.2	3.72

The generalized decrease of both BP and CFL for both treated scenarios Sc1 and Sc2 was not symmetric. The decreased experienced by Sc2 was higher than Sc1 (Figure 26). Being more important the differences of the average CFL in Sc2 and Sc1 (Table 21).

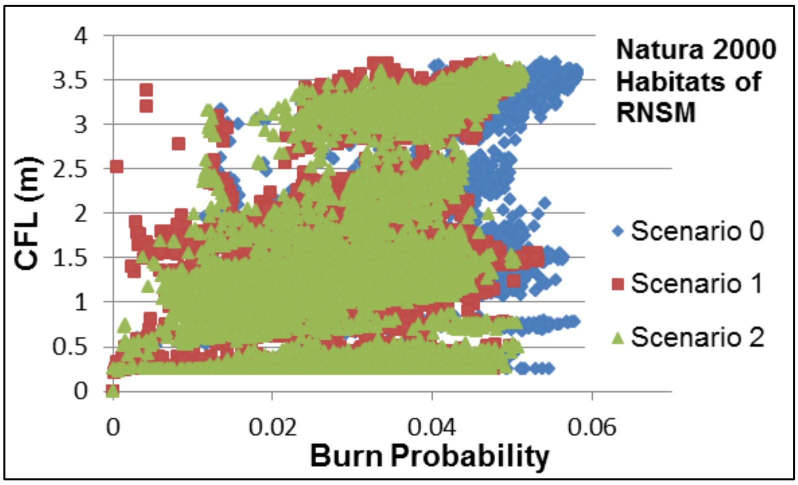

Fig 26. Scatter plots of burn probability *vs.* conditional flame length (CFL) for Scenario 0, Scenario 1 and Scenario 2

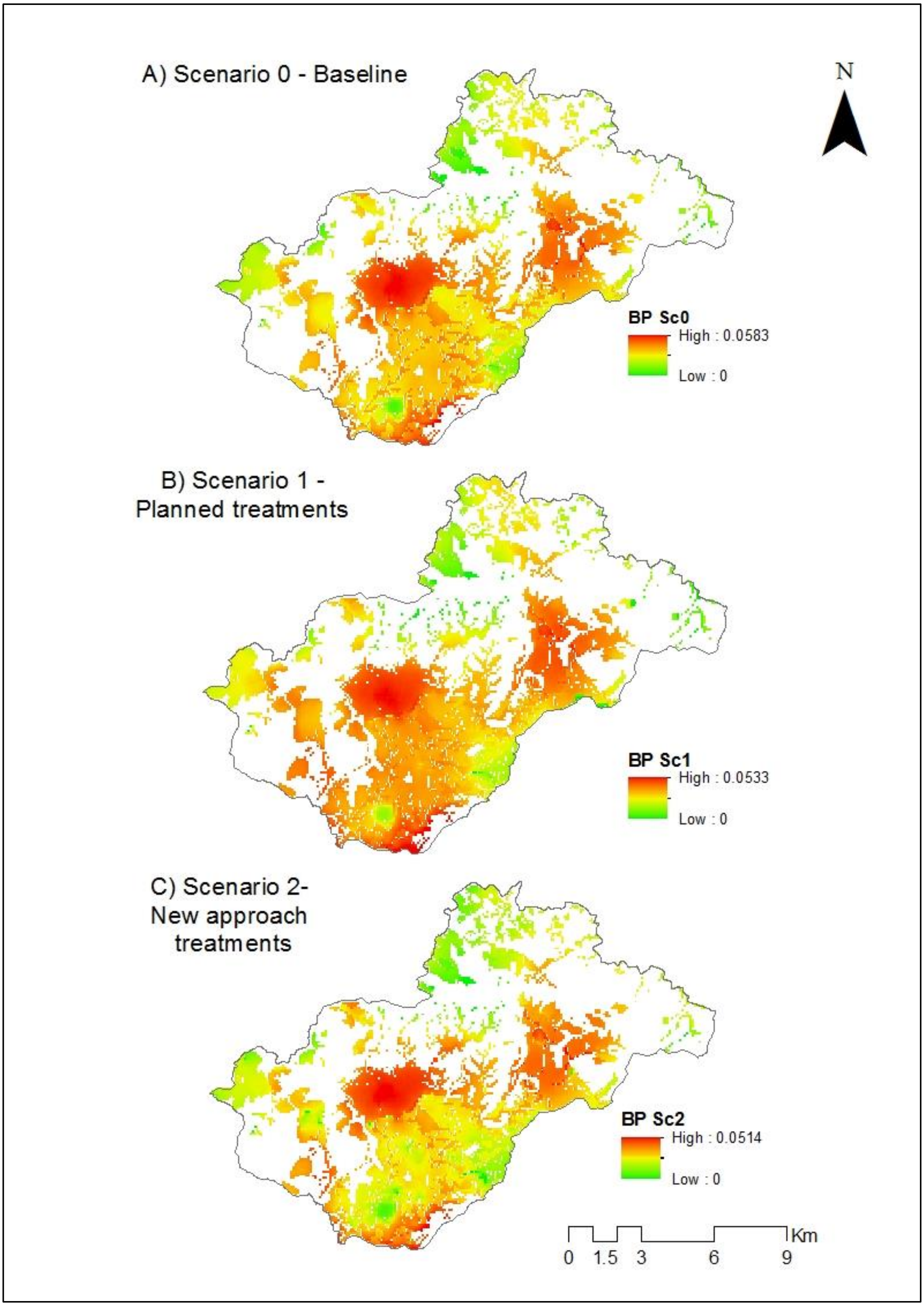

Fig 27. Effects of fuel treatments over Scenario 0 (A), fuel managed Scenario 1 (B) and Scenario 2 (C) on burn probability within the Natura 2000 Network of Reserva Natural of Serra of Malcata.

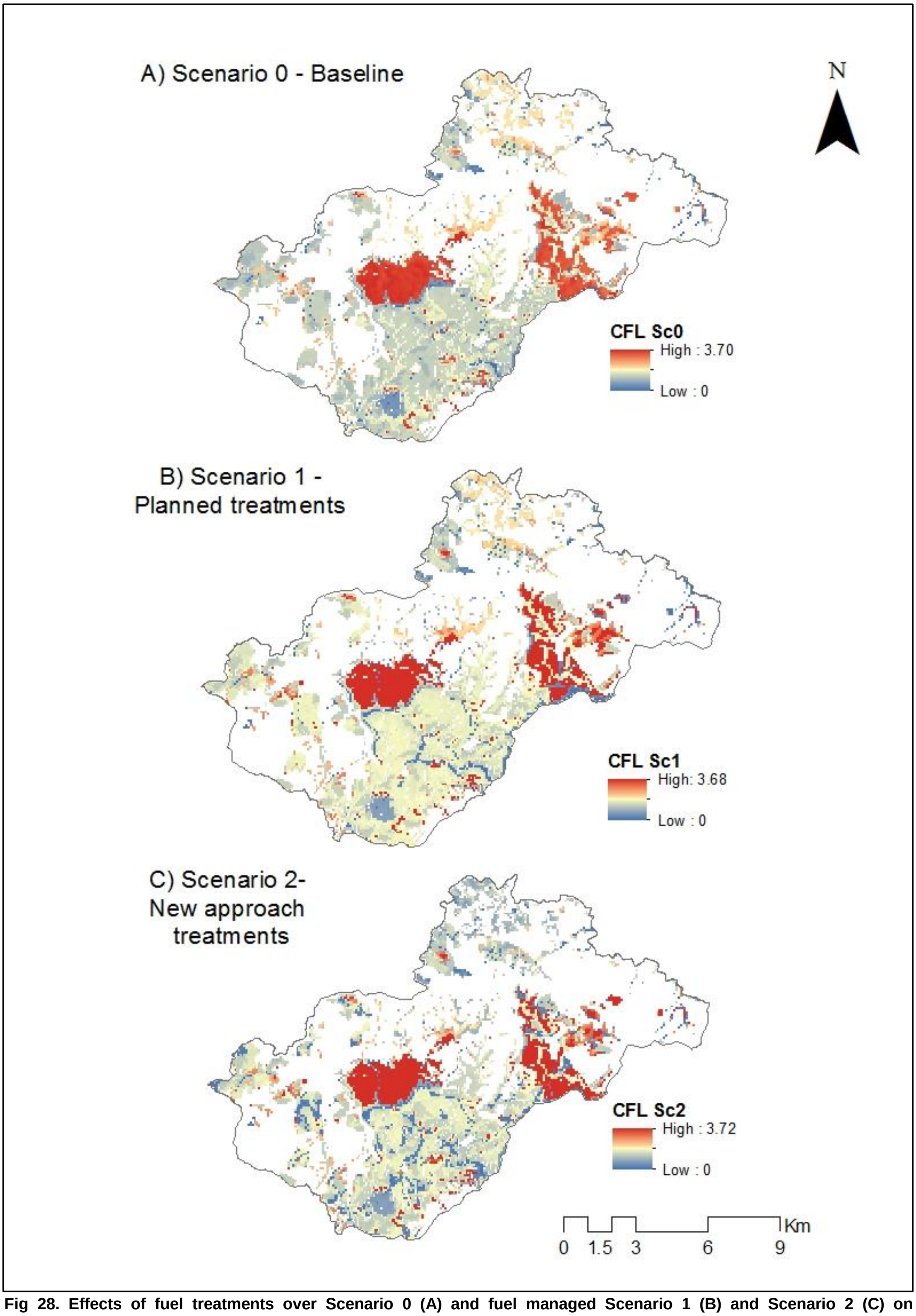

Fig 28. Effects of fuel treatments over Scenario 0 (A) and fuel managed Scenario 1 (B) and Scenario 2 (C) on conditional flame length (CLF) in meters within the Natura 2000 Network of Reserva Natural of Serra of Malcata.

5.3.1. Natural eutrophic lakes/Water courses of plain to montane levels/Thermo-Mediterranean and pre-steppe scrub/Alluvial forest with *Alnus glutinosa* & *Fraxinus excelsior* (3150, 3260, 91E0 and 5330)

This protected habitat types are composed by the associations of four different Natura 2000 protected habitats. Burn probability ranged from 0 to 0.0542 with an average of 0.0522 for the baseline scenarioSc0 whereas treated scenarios, Sc1 and Sc2, registered lower average values of 0.0418 and 0.0460, respectively (Table 22). In percentages, treatments of Sc1 produced a higher reduction of BP than in Sc2 with a 19.8% and 11.8% reduction respected to the valued observed in the scenario 0. In case of the Conditional flame length, all scenarios had similar CFL values that ranged between 2.02 to 2.05 m. Both Sc1 and Sc2 registered the increase of CFL respected to Sc0 although this increase was insignificant (Table 22). Comparing BP and CFL, the performance of the treatments showed that BP decreased meanwhile CFL was maintained (Figure 29A).

Table 22. Burn Probability (BP) and Conditional Flame Length (CFL) statistics of simulated scenarios (Sc0, Sc1 and Sc2) and their differences at pixel-level between scenarios within Natura 2000 habitat types 3150, 3260, 91E0 and 5330. Differences: Increase (+), decrease (-).

Treat.	Mean BP	ΔBP	Diff. (%)	BP Max	Mean CFL (m)	ΔCFL	Diff. (%)	CFL Max (m)
Sc0	0.0522			0.0542	2.02			2.11
Sc1	0.0418	0.010	-19.8	0.0445	2.04	-0.019	+0.9	2.14
Sc2	0.0460	0.006	-11.8	0.0475	2.05	-0.028	+1.4	2.00

5.3.2. European dry heaths (4030)

This Habitat Natura 2000 is characterized by being one of the most pyrophytic fuel models. Average BP of Sc0 was 0.041 what it means that on average each pixel burned 2050 times and the maximum BP was 0.058. Considering fuel treatments done in both Sc1 and Sc2, the average BP decreased around the 13% and 19% respectively; reaching BP values of 0.035 and 0.033. Average conditional flame length decreased as well as BP. Average CFL values changed from 1.89m of Sc0 to 1.78m registered in Sc1 and 1.64m in Sc2 with a decreased of 5.9 and 13.5% respectively (Table 23).

Table 23. Burn Probability (BP) and Conditional Flame Length (CFL) statistics of simulated scenarios (Sc0, Sc1 and Sc2) and their differences at pixel-level between scenarios within Natura 2000 habitat habitat types 4030. Differences: Increase (+), decrease (-).

Treat.	Mean BP	ΔBP	Diff. (%)	BP Max	Mean CFL (m)	ΔCFL	Diff. (%)	CFL Max (m)
Sc0	0.041			0.058	1.89			3.70
Sc1	0.035	0.0053	-13.0	0.053	1.78	0.11	-5.9	3.68
Sc2	0.033	0.0077	-19.0	0.051	1.64	0.26	-13.5	3.72

Attending to the relationship between BP and CFL within 4030 habitat, there was an appreciable decrease of BP for both treated scenarios while CFL decreased more slightly (Figure 29B). Besides that, this Natura 2000 habitat presented high BP and CFL variability.

5.3.3. Thermo-Mediterranean and pre-desert scrub (5330)

Burn probabilities of Sc1 and Sc2 decreased if compared with Sc0 with a reduction of the 10% and 15.9% respected to the baseline scenario. Average BP values ranged between the highest 0.0371 of Sc0 and the lowest, 0.0312 obtained for Sc2 (Table 24). Conditional flame lengths suffered the reduction of its average from Sc0 to Sc1 and Sc2; having the biggest decrease of CFL the last one with a 3.4% reduction of the flame length. Both CFL reductions were insignificant (Table 24). If compared the BP and CFL relationships among the different scenarios (Figure 29C), it was clearly visible the shift toward a lower BP but not followed by the decrease of CFL.

Table 24. Burn Probability (BP) and Conditional Flame Length (CFL) statistics of simulated scenarios (Sc0, Sc1 and Sc2) and their differences at pixel-level between scenarios within Natura 2000 habitat types6130. Differences: Increase (+), decrease (-).

Treat.	Mean BP	ΔBP	Diff. (%)	BP Max	Mean CFL (m)	ΔCFL	Diff. (%)	CFL Max (m)
Sc0	0.0371			0.051	1.72			3.24
Sc1	0.0334	0.0037	-10.0	0.040	1.70	0.02	-1.1	3.28
Sc2	0.0312	0.0059	-15.9	0.043	1.66	0.06	-3.4	3.20

5.3.4. Calaminarian grasslands of the *Violetalia calaminariae* (6130)

Burn probability was barely affected by the treatments applied in Sc1 and Sc2 with reductions lower than 2.5%. CFL was also hardly affected by treatments, experiencing reductions of 0.2 and 1% respected to Sc0 (Table 25). In general, both average BP and CFL for this protected habitat showed one of the lowest BP and CFL values if compared with other Natura 2000 areas. Figure 29D showed that treatments caused the reduction of both CFL and BP; however, this reduction was almost insignificant.

Table 25. Burn Probability (BP) and Conditional Flame Length (CFL) statistics of simulated scenarios (Sc0, Sc1 and Sc2) and their differences at pixel-level between scenarios within Natura 2000 habitat types6130. Differences: Increase (+), decrease (-).

Treat.	Mean BP	ΔBP	Diff. (%)	BP Max	Mean CFL (m)	ΔCFL	Diff. (%)	CFL Max (m)
Sc0	0.0261			0.027	0.277			0.289
Sc1	0.0254	0.0006	-2.4	0.027	0.276	0.001	-0.2	0.286
Sc2	0.0233	0.0027	-0.5	0.024	0.274	0.003	-1.0	0.284

5.3.5. Lowland hay meadows (6510)

Average burn probability of baseline scenario ranged from 0 to 0.0321 with an average BP value of 0.0261 what represent one of the lowest BP value among the protected ecosystems. Burn probabilities varied in different way according to the treated scenario. In fact, treatments done in Sc1 produced the reduction of almost the 44% of the BP while Sc2 just reduced a 4%. This could be produced by the different allocation of fuel treatments among Sc1 and Sc2 (Table 26).

Conditional flame length had a similar tendency than the followed by BP. Treatments applied in Sc1 reduced the 11.7% of the flame length respected to Sc0. In case of Sc2, there was not almost any decrease compared baseline scenario (Table 26).

Table 26. Burn Probability (BP) and Conditional Flame Length (CFL) statistics of simulated scenarios (Sc0, Sc1 and Sc2) and their differences at pixel-level between scenarios within Natura 2000 habitat types 6510. Differences: Increase (+), decrease (-).

Treat.	Mean BP	ΔBP	Diff. (%)	BP Max	Mean CFL (m)	ΔCFL	Diff. (%)	CFL Max (m)
Sc0	0.0216			0.0321	0.52			3.10
Sc1	0.0121	0.0095	-43.9	0.02172	0.46	0.061	-11.7	2.77
Sc2	0.0208	0.0008	-3.9	0.02958	0.52	0.002	-0.4	3.04

Figure 29E showed clearly that treatments of Sc1 were more successful than the ones done in Sc2 for this habitat. The dispersion graph showed that in general for all scenarios, the BP and CFL were relatively low. In case of Sc1, compared with the others, the fire exposure decreased more intensely.

5.3.6. Siliceous rock with pioneer vegetation of the *Sedo-Scleranthion* or of the *Sedo albi-Veronicion dillenii* (8230)

In general, this Habitat Natura 2000 showed low values of BP ranged between the highest value, 0.0067, represented by Sc0 and the lowest value, 0.0043, took by Sc2 (Table 27). Both Sc1 and Sc2 experienced a similar BP decrease, with the reduction of BP value in 30% and 35% respectively from the baseline scenario. Regarding to the CFL, fuel treatments only produced the decreased of flame length value for Sc1 with a reduction of almost 31%. However, treatments done with the Sc2 did not produce any difference.

Confronting BP and CFL distribution (Figure 29F), it was clearly visible the differences of the treatments applied in Sc1 and Sc2. The treatments done in the former produced both the decrease of BP and CFL whereas in the latter there was not any effect over the CFL.

Table 27. Burn Probability (BP) and Conditional Flame Length (CFL) statistics of simulated scenarios (Sc0, Sc1 and Sc2) and their differences at pixel-level between scenarios within Natura 2000 habitat types8230. Differences: Increase (+), decrease (-).

Treat.	Mean BP	ΔBP	Diff. (%)	BP Max	Mean CFL (m)	ΔCFL	Diff. (%)	CFL Max (m)
Sc0	0.0067			0.0067	1.17			1.17
Sc1	0.0047	0.0020	-30.2	0.0047	0.81	0.361	-30.9	0.81
Sc2	0.0043	0.0024	-35.3	0.0043	1.17	0.002	-0.2	1.17

5.3.7. Siliceous rock with pioneer vegetation of the *Sedo-Scleranthion* or of the *Sedo albi-Veronicion dillenii/Quercus ilex* and *Quercus rotundifolia* forests (8230 & 9340)

This habitat Natura 2000 type showed an interesting behavior because the different treatment applied for the different scenarios gave two opposite results. In both case, there were the reduction of the average BP of 0.0269 and CFL with 1.82m observed in baseline scenario. Sc1 suffered the highest reduction of BP with a decrease of 30% whereas the same scenario almost did not reduce CFL (0.7%). On the other hand, Sc2 produced the half of the BP reduction generated by Sc1 with the 15.8% but CFL decreased much more if compare to Sc1 (Table 28).

Figure 29G showed that treatments in both scenarios decreased the BP considerately with respect to Sc0. However, it was also clearly visible that scenario 2 accompanied the decrease of BP with a large decrease of CFL.

Table 28. Burn Probability (BP) and Conditional Flame Length (CFL) statistics of simulated scenarios (Sc0, Sc1 and Sc2) and their differences at pixel-level between scenarios within Natura 2000 habitat types 8230 and 9340. Differences: Increase (+), decrease (-).

Treat.	Mean BP	ΔBP	Diff. (%)	BP Max	Mean CFL (m)	ΔCFL	Diff. (%)	CFL Max (m)
Sc0	0.0269			0.04348	1.82			2.34
Sc1	0.0187	0.0082	-30.4	0.03332	1.81	0.013	-0.7	2.46
Sc2	0.0226	0.0043	-15.8	0.03944	1.43	0.388	-21.3	2.43

5.3.8. Galicio-Portuguese oak woods with *Quercus robur* and *Quercus pyrenaica* (9230 pt2)

Average burn probability of Sc0, 0.0225, decreased in both scenarios due to fuel treatments. However, the highest average BP reduction was achieved by the Sc2 instead than Sc1 with a substantial difference among them (Table 29). The BP reduction was around the 10.5% for Sc1 whereas Sc2 achieved the reduction of 27.5%.

Regarding to conditional flame length, it followed the same pattern described by BP, Sc2 decreased significantly the CFL from average flame length of 1.39m to flame length of 1.04m (Table 29).Plotting BP *vs.* CFL, it was possible to corroborate that Sc2 was more effective than Sc1 for decreasing both BP and CFL related to Sc0 (Figure 29H).

Table 29. Burn Probability (BP) and Conditional Flame Length (CFL) statistics of simulated scenarios (Sc0, Sc1 and Sc2) and their differences at pixel-level between scenarios within Natura 2000 habitat types 9230. Differences: Increase (+), decrease (-).

Treat.	Mean BP	ΔBP	Diff. (%)	BP Max	Mean CFL (m)	ΔCFL	Diff. (%)	CFL Max (m)
Sc0	0.0225			0.03996	1.39			2.42
Sc1	0.0201	0.0024	-10.5	0.03416	1.35	0.044	-3.1	2.37
Sc2	0.0163	0.0062	-27.5	0.03394	1.04	0.355	-25.5	2.13

5.3.9. Castanea sativa woods (9260)

Average burn probability decreased due to fuel treatment actions done in Sc1 and Sc2, the reduction of the average burn probability in percentage was 16.5% and 10.7% related to the baseline scenario 0 in which each pixel burned on average 1225 times or a BP 0.0245. However, CFL was hardly affected by the treatments with not visible changed (Table 30) with decreases of less than 1cm on the average flame length. The decrease experienced by both treated scenarios on the average BP was not corresponded by a simultaneous CFL reduction (Figure 29I).

Table 30. Burn Probability (BP) and Conditional Flame Length (CFL) statistics of simulated scenarios (Sc0, Sc1 and Sc2) and their differences at pixel-level between scenarios within Natura 2000 habitat types 9260. Differences: Increase (+), decrease (-).

Treat.	Mean BP	ΔBP	Diff. (%)	BP Max	Mean CFL (m)	ΔCFL	Diff. (%)	CFL Max (m)
Sc0	0.0245			0.0352	1.28			2.10
Sc1	0.0204	0.0040	-16.5	0.0297	1.27	0.016	-1.2	2.07
Sc2	0.0218	0.0026	-10.7	0.0288	1.27	0.013	-1.0	2.06

5.3.10. Quercus ilex and Quercus rotundifolia forests (9340)

Average burn probability for this habitat type was one of the most highest among the Natura 2000 network within RNSM (Table 31). The average BP for Sc0 was 0.0379 and ranged between 0 and 0.05222, being this habitat type one of the most variable within all the Natura 2000 habitats (Figure 29J). Fuel treatments done in Sc1 and Sc2 produced the decrease of the 11.4% and 19.4% on the average BP. Regarding to the average conditional flame length, fuel treatments of Sc1 and Sc2 also reduced the average CFL. Although the reduction produced by Sc2 is significantly bigger than in Sc1, the general reduction of CFL respected to Sc0 is small.

Table 31. Burn Probability (BP) and Conditional Flame Length (CFL) statistics of simulated scenarios (Sc0, Sc1 and Sc2) and their differences at pixel-level between scenarios within Natura 2000 habitat types 9340. Differences: Increase (+), decrease (-).

Treat.	Mean BP	ΔBP	Diff. (%)	BP Max	Mean CFL (m)	ΔCFL	Diff. (%)	CFL Max (m)
Sc0	0.0379			0.0522	1.50			3.53
Sc1	0.0336	0.0043	-11.4	0.0481	1.48	0.017	-1.1	3.55
Sc2	0.0305	0.0074	-19.4	0.0446	1.39	0.107	-7.1	3.52

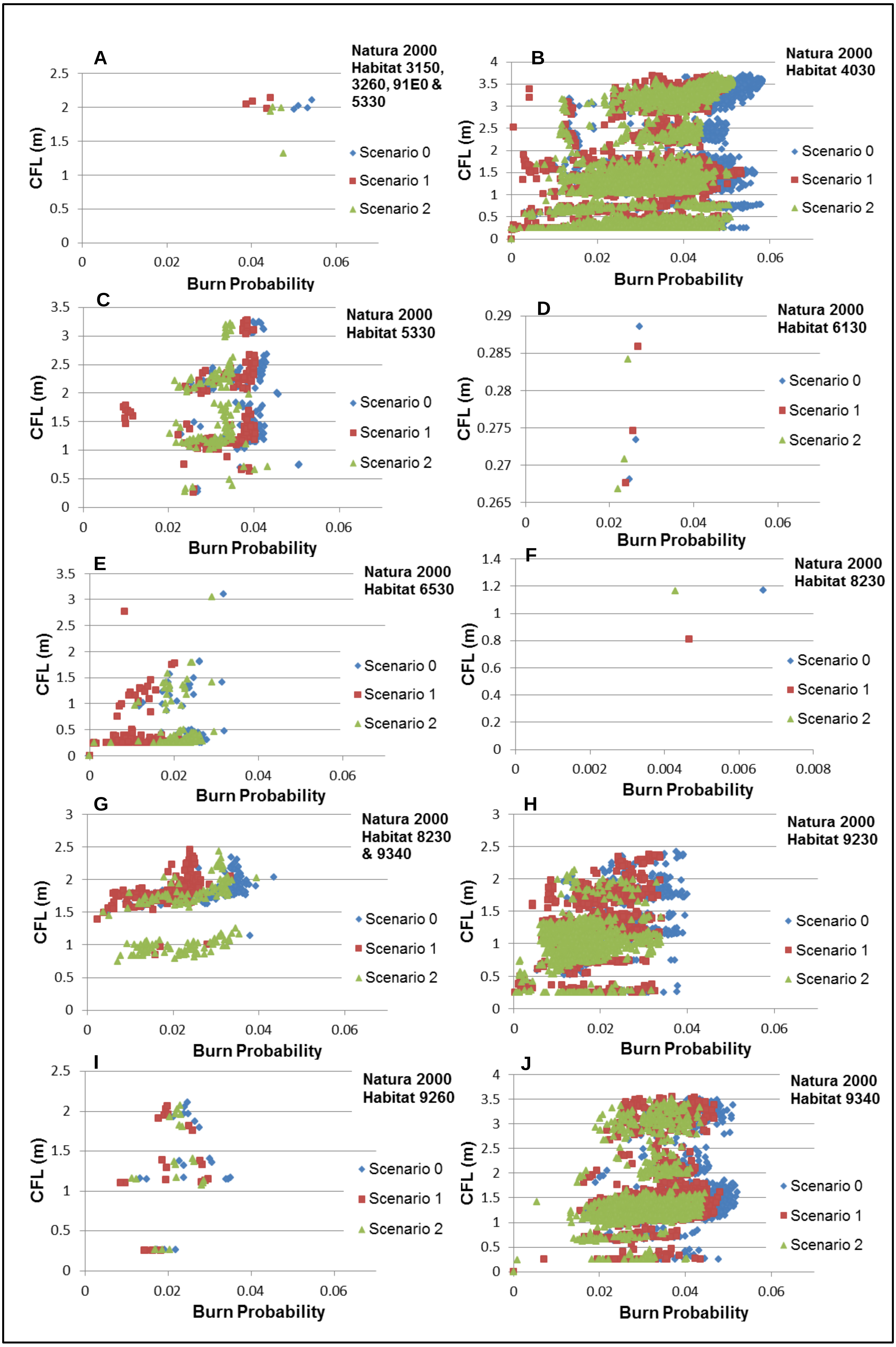

Fig 29. Scatter plots of burn probability *vs.* conditional flame length (CFL) for Scenario 0, Scenario 1 and Scenario 2 in the different Habitat Natura 2000 (numerated with letters A to J) localized within RNSM.

6. DISCUSSION

The main objective of this work was to compare how different management scenarios in a protected area with strong limitation for active management, may reduce risk of wildfire while simultaneously maintaining or enhancing conservation goals. For that reason, wildfire exposure was assessed and compared in three different scenarios by using burn probability modelling, which made possible to capture exposure components, Burn probability (BP) and Conditional Flame Length. This method has been widely used both USA and Mediterranean region for approaching fire exposure (Ager and Finney, 2009; Ager et al., 2014a, 2013, 2012; Bar Massada et al., 2009; Kalabokidis et al., 2013; Salis et al., 2013) or analyzing fuel treatment performance (Ager et al., 2007, 2006).

Contrary to previous methods which have quantified wildfire likelihood with few predetermined ignition location, burn probability modelling provides more robust measures of wildfire likelihood (Salis et al., 2013) thanks to the development of fire simulators as RANDIG which incorporates MTT algorithm (Ager et al., 2006). These make feasible to map and analyze fire risk exposure and to eliminate bias due to the assumption of small number of ignition points (Salis et al., 2013). However, it is convenient to point that simulation outputs and, in turn, the results obtained will be always uncertain and bias respected to the reality, since wildfires are highly stochastic natural phenomena (Thompson and Calkin, 2011). Therefore, results should be taken as general information related to wildfire (Salis et al., 2013) and use carefully. When simulation modelling is being used, certain issues arise related to input parameters (*e.g.* fuel model characterization, moisture content and weather description), model validation (*e.g.* burn period definition) or limitations done in the simulation processes could affect the performance of fuel treatments.

Fuel treatments associated to Sc1 and Sc2 produced changes on the contribution that the different fire size classes had over the number of ignition and burned area. In both cases, treatments achieved their prescribed objectives because they reduced the contribution that large wildfires (over 2000 ha) had within RNSM in terms of number of ignitions and burned area. This loss was counterbalanced by the increase of number of ignitions and burned area represented by smaller fire size classes. Although, these changes were higher for Sc2 than Sc1, there were not large differences between them. However both scenarios contributed to reinforce the idea that prescribed burning mitigates unplanned fire extent (Boer et al., 2009), since fire extent of unplanned fire was reduced by shifting percentage of burned area done by large to small fire size classes.

Fire exposure was reduced by the treatments applied both in Sc1 and Sc2 respected to the baseline scenario. On average, both treated scenarios were somehow effective to reduce burn probability and conditional flame length. Nevertheless, in overall, there were not great differences among average burn probabilities and conditional flame length between Sc1 and Sc2. A deeper insight of the results obtained by BP and CFL classes showed both, Sc1 and Sc2, reduced the highest BP classes meanwhile the major reductions for CFL were observed for short flame lengths (0 to 1.2 m). The performance of the treatments applied pointed that despite of the effectivity in wildfire likelihood reduction; fuel treatments were insufficient over fire severity. The maintenance of almost similar average on large flame length is translated in the maintenance of almost the same danger, as flame length is a measure of fire hazard (Ager et al., 2010). If instead of average BP and CFL values, we had a look over the spatial variation produced over the different BP and CFL classes, we observed that lower BP classes increased their extension due to the decrease of the highest BP classes. However, this spatial variation was not followed by CFL which only experienced changes on the two shortest flame lengths, being almost not affected flame lengths over 2.4 m. In general, treatments applied in Sc2 produced a higher exchange of surfaces from high BP and CFL classes to lower BP and CFL than the ones applied in Sc1.

In general, fuel treatments of Sc2 showed a similar performance than those applied into Sc1 for reducing the extension of burned areas and fire exposure in the whole preserved area. The reduction of fire exposure and unplanned wildfires extent, and in turn fire risk, is a causative result achieved by fuel management through the use of prescribed burning (Agee and Skinner, 2005). However, although it seemed that Sc2 had more or a similar effect than Sc1, neither of them achieved a significant reduction of fire exposure components, BP and CFL, respected to the baseline scenario as good as the ones obtained in other similar works of Ager et al. (2006) or Ager et al. (2007), where the average burn probability reduction achieved were sensitively higher than the one of the present work for the same percentage of the terrain treated. Nevertheless, it is necessary to point that this comparison could be not worthy to make since the weight of the factors that condition fire behavior could be different for each area could produce different results.

However, if taking into account the spatial exchange between BP and CFL classes, the shift of burn probability from higher to lower classes was pretty visible and, somehow, this would justify, in part, a better performance of Sc2. However, the no reduction of CFL, in any of the treated scenarios of the spatial extension from high to small flame length classes ones, counterbalanced the good results due to large areas with large flame length (>2.4m) are maintained and the suppression capabilities would be inefficient due to high fire intensity (Andrews et al., 2011).

The little effect of fuel treatments over fire exposure and unplanned fire extent could be attributable to some limitations and assumptions of the simulation process developed. The omission of fire suppression forces could have contributed to reduce the potential effects of fuel treatments over fire exposition and unplanned fire extension (Boer et al., 2009). In addition, the randomly placement of fuel treatment done in Sc2 could also have limited the performance of fuel treatments, since random location required twice the treatment rate of optimally place fuel treatments to produce same predicted fire growth reduction (Finney et al., 2007), which directly affect fire exposure. Therefore the spatial pattern optimization of fuel treatments should be considered as a priority, in order to improve fuel treatment performance, since the spatial distribution of fuel treatment is a key determinant of the annual extent of unplanned fires (Boer et al., 2009).

Previous works, where different fuel treatments were assessed, showed that the best results, in terms of burn probability reductions, were achieved when 20% of the total area was treated. Since major percentages of area treated did not produced a substantially higher reduction (Ager et al., 2006; Calkin et al., 2011). This could drive to the conclusion that the area treated in both Sc1 and Sc 2 should be reached the 20% instead of the 13% of the total area for achieving notably better results.

The randomly fire ignition location used for the simulations should be also considered as a source of limitations. Although Salis et al. (2013) had similar mean BP values between simulations in which historical ignitions locations and randomly locations were used, there are several works that have pointed different variables that explains the spatial distribution of fire ignitions, such as distance to roads, population density, land cover or elevation (Catry et al., 2009; Chuvieco et al., 2010). For that reason, the fire ignition risk grid of Portugal developed by Catry et al. (2009) should have been used to obtain reliable results which captured better the reality.

Reserva Natural of Serra Malcata has been characterized by almost inexistent large forest fires historial. Fire suppression has reduced wildfires effect into small burned areas surfaces. This fact has produced problems for validating the simulation, a crucial step for getting plausible outputs (Cruz and Alexander, 2010). In this case, it was assumed a burn-period of 24h as it was the period of time that was better fitting between historical large wildfires and simulations. However, this assumption could have produced the distortion of the results producing the overestimation or underestimation of the fire exposure components.

The characterization of fuel models was another important step faced during the construction of the fuel model scenarios. The definition of fuel models used in this work was based on the land cover information contained in the Corine Land Cover and COS 2007, a method already applied elsewhere (Salis et al., 2013). However, in this case, the use of different land cover information sources with mismatching information between them could have produced a bad characterization of the fuel models and, in turn, the underestimation or overestimation of the simulation outputs. In fact, simulations showed that for a burn period of 24h, the maximum burned area reached smaller surfaces than the ones that it could reach by *in-situ* observations, since the fuel continuity detected within RNSM is really high. However, fuel models are always difficult to calibrate and are rarely to validate with the observed behavior (Arca et al., 2007). In addition, not only a bad fuel model characterization would be able to produce errors. The rasterization of the fuel model information from vector information into a pixel grid size of 90x90m could be also a source bias. Fuel treatments were designed in a vector format file and some of them had small dimensions; meaning that when they were rasterized, it could have been generated the omission of fuel model changes.

Besides the problems that could arise from a bad characterization of fuel models or validation issues, fire behavior simulators have some intrinsic limitations. In case of FlamMap and Randing, weather conditions and moistures are taken as constants (Finney, 2006b); this fact limits outputs given by simulations since weather conditions and fuel moisture can vary through time.

Finally, it is necessary to point the assumptions and limitations that arise with the wind data used for the simulations. The data used explains the overall wind pattern over RNSM, however, this pattern would vary when it is zoom into the RNSM; that is, if it had been taking into account the local wind patterns of Malcata. The use of WindNinja software could have improve the wind data input and in turn the simulator outputs, BP and CFL, for doing a better fire exposure assessment.

6.1. Fire exposure within Natura 2000 network

Regarding to fire exposure within Natura 2000 Habitats, the treatments applied in Sc1 and Sc2 reduced both average BP and CFL. If these two are compared, the reduction generated by the treatments applied in Sc2 produced a more significant decrease than those of Sc1 for CFL and BP. This generalized decrease tendency varied according to the different Habitats that compound the Natura 2000 network in RNSM. There were cases such as habitat 4030, 5330, 9340 and 9230 that Sc2 reduced more notably fire exposure than Sc1 whereas others registered larger reductions of both BP and CFL for Sc1 such as in 6510, of one of them like in 8230-9340 or in which neither of the treated scenarios produced any reduction. However, the different spatial extent of the Habitats Natura 2000 of RNSM should be considered when we compare the performance of both treated scenarios and which produced better results. Attending to this, Sc2 produced biggest reduction of fire exposure by far, since it was the scenario that produced the major decreases of BP and CFL in the largest protected Natura 2000 Habitats. This reinforced the results of the general statistics related to average BP and

CFL and pointed that Sc2 fuel treatments had a better performance than Sc1 ones related to Natural 2000 network. However, although a better performance of fuel treatments was observed within Natura 2000 ecosystems, the limitations above explained related to the general low performance of fuel treatments should be considered in this case, too.

The highest burn probabilities and conditional flame values were located within dense shrubland areas, the largest land cover within RNSM. They are considered as the most fire-prone land-cover type in Portugal (Marques et al., 2011). The little fire exposure reduction of this land cover drove to conclude that the allocation of fuel treatment should have been other or that a spatial optimization of the treatments would be improved their performance, as previously mentioned. In addition, highly valuable habitats formed by *Q.ilex-A. unedo* and *Q. pyrenaica*, which indeed have a protected status, showed high average burn probabilities and flame lengths. These ecosystems usually had a shrubland-type plant community structure what conferred them a high prone to fire (Rego and Silva, 2014). The high fire exposure of these high valuable ecosystems would support the inclusion of protected areas within fuel management plans and the results obtained in this work would reinforce this idea. The Sc2, in which some protected areas of Natura 2000 habitats were treated with low intense fuel treatments, showed a notably decrease of fire exposure if compared with treatments done in Sc1. Therefore, although fuel treatments application within preserved areas continue to be controversial, at medium- and long-term benefits in conservation purposes by decreasing wildfire risk would support the adoption of fuel treatment actions within preserved areas (Roloff et al., 2005).

The use of fuel treatment in general and prescribed burnings in particular within preserved area is predominantly perceived by the society as inappropriate or inconceivable. However, prescribed burning has been already used as a tool not only promoting nature conservation of species adapted to wildfires such as Scot pine (*Pinus sylvestris*) in Sweden (Montiel and Kraus, 2010), Ponderosa pine (*Pinus ponderosa*) in USA (Metlen and Fiedler, 2006) or Spanish heathlands (*Erica australis*) (Fernández et al., 2013) in Spain but also for restoring or managing habitat for fauna such as is the case of wild rabbits (*Oryctolagus cuniculus*) in southern Spain (Moreno and Villafuerte, 1995), red deer (*Cervus elaphus*) in UK (Bruce et al., 2014) or the northern Idaho ground squirrel (*Urocitellus brunneus brunneus*) in USA (Suronen and Newingham, 2013). Many of these examples showed good results provided by the use of controlled fire for achieving conservation goals and this supports the need to transmit to the society the benefits that its use can bring.

7. CONCLUSION

In Portugal, as in other Mediterranean countries, wildfires are a major concern since annually produce economic, social and environmental losses. This concern increases even more when protected areas are affected. For that reason, the detection of the most susceptible areas and their treatment should be considered as a vital step for mitigating wildfire effects. This fact justified the need to include wildfire management into policy-making processes through use of wildfire risk assessments.

In this context, simulation modelling approach is increasingly being used for facing wildfire issues, because of its enormous capabilities for assessing and mapping wildfire risk and exposure and because of their big potential use for prioritizing the allocation of fuel treatments or for assessing their performance. However, their uses do not exclude them of some source of uncertainties intrinsic to wildfire which make that their results should be taken as general information.

Fuel management through the implementation of fuel treatments are necessary actions for decreasing wildfire risk since the other two factors that influence fire behavior, climate and topography, are beyond of human control. The effectively of fuel treatments have been fully demonstrated when they have been implemented; however, the application of them into preserved areas seems to continue to be controversial. The potential benefit that the inclusion of fuel treatment within protected habitat can produce at medium- and long-term should be taken into account because low intense interventions could reduce the potentiality of large wildfire and in turn mitigate their effects, benefiting the conservation and reducing wildfire risk.

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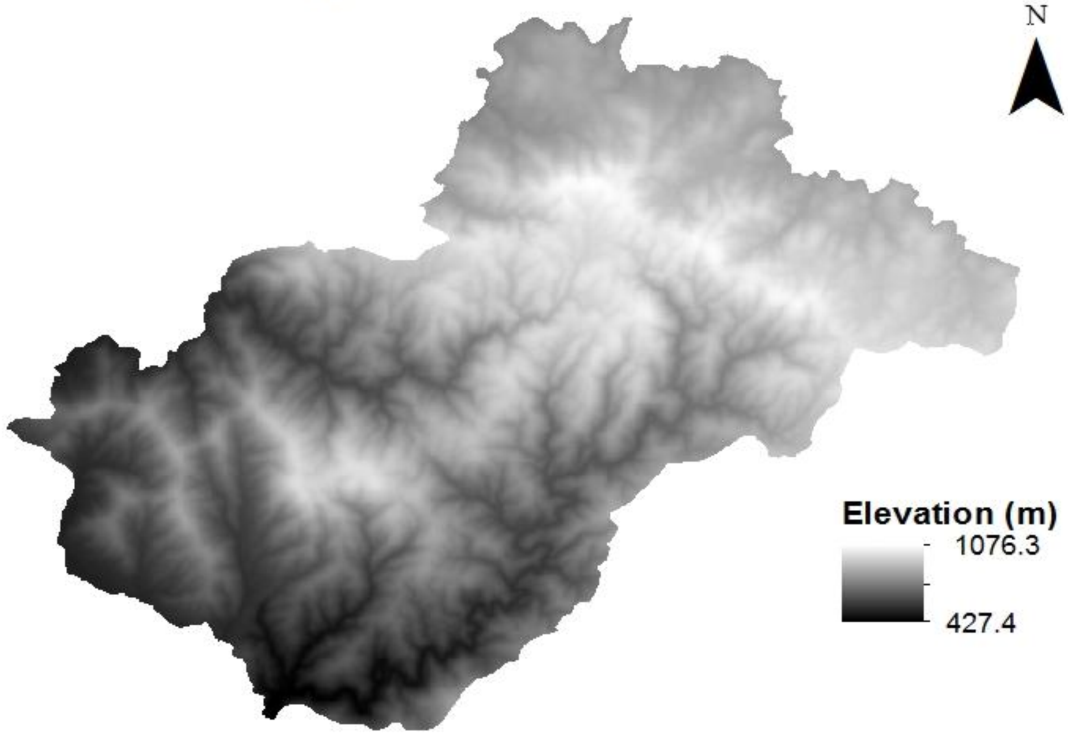
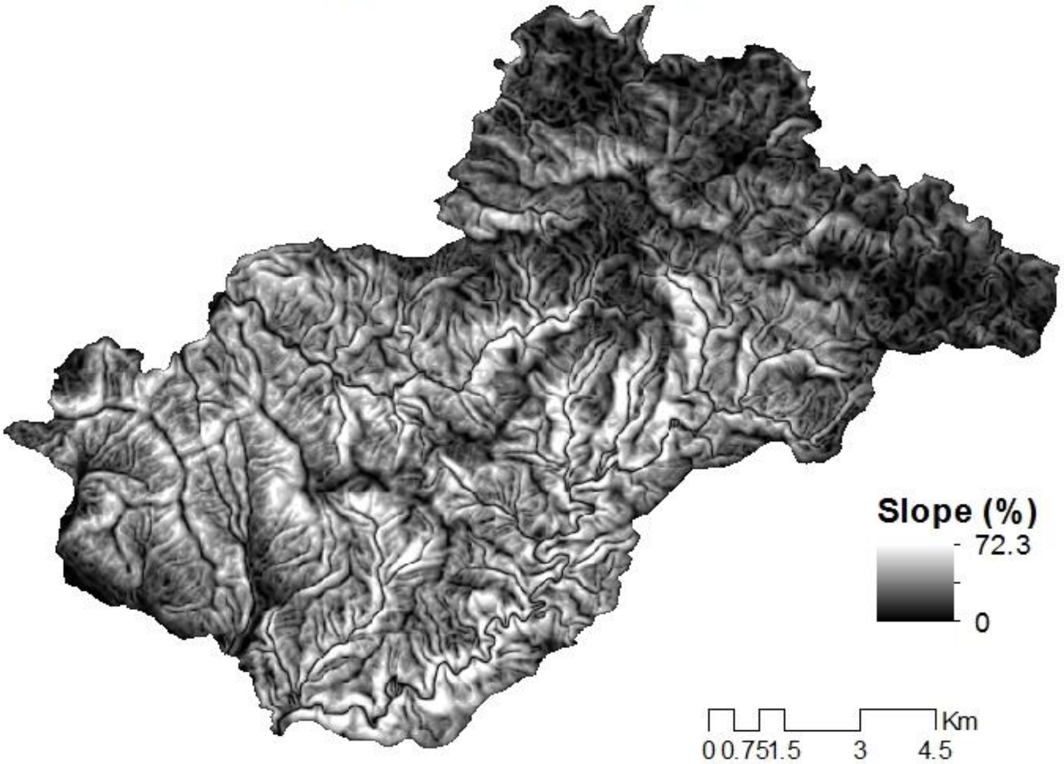
ANNEX I. Elevation, slope and aspect maps

Elevation, slope and aspect maps of Reserva Natural of Serra Malcata. They were used as inputs to generate the landscape file needed to do simulations.

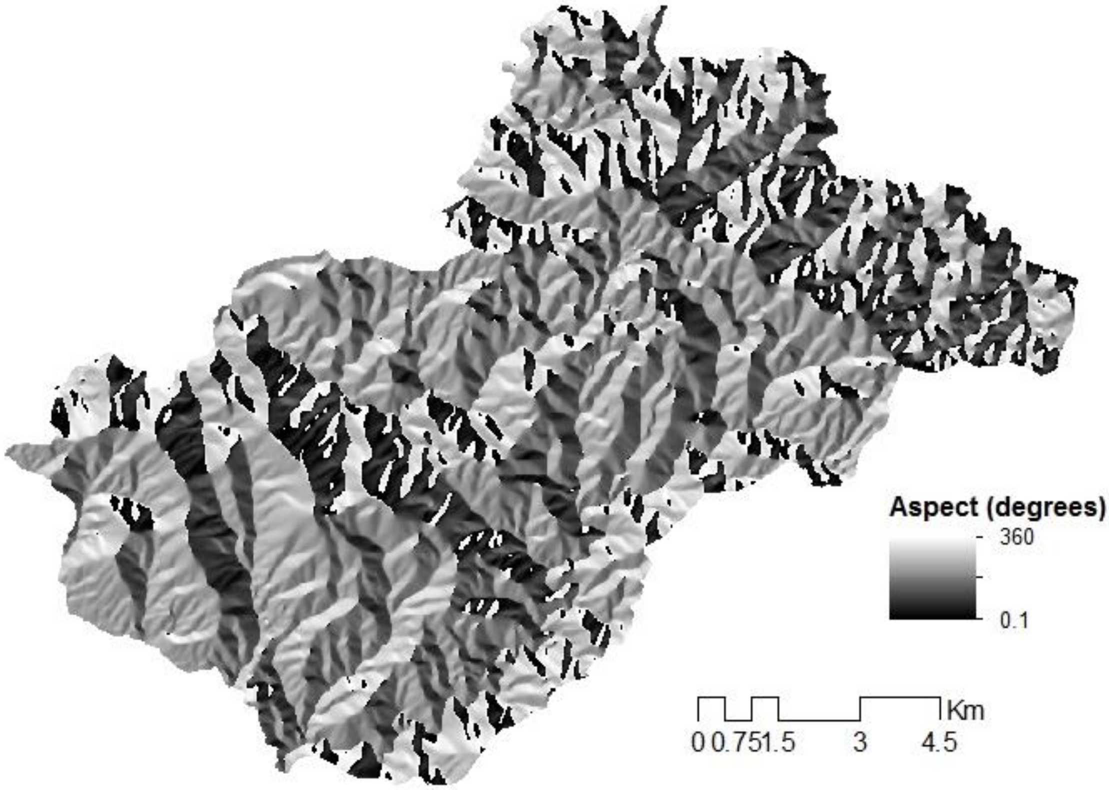
Elevation map of Reserva Natural of Serra Malcata



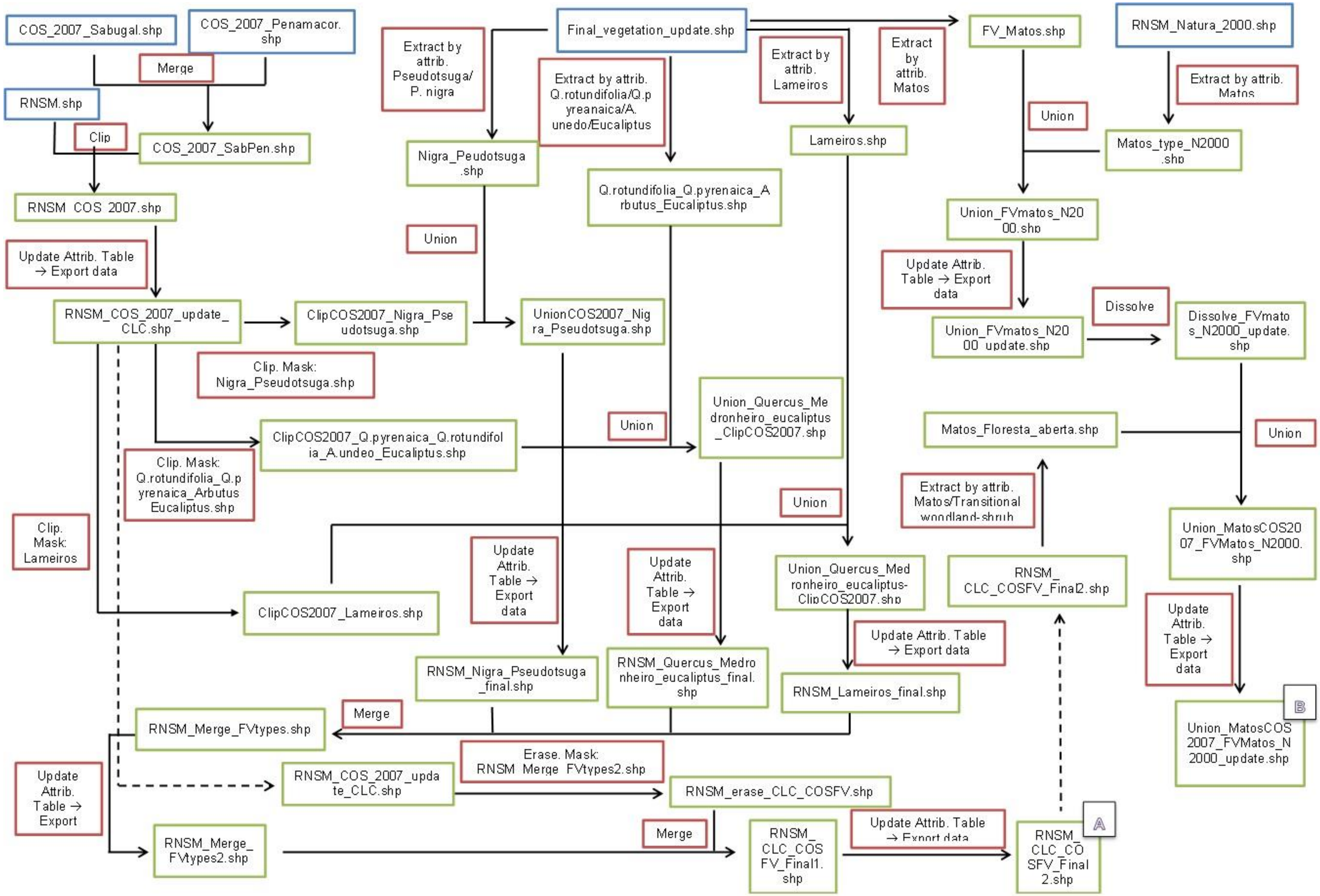
Slope map of Reserva Natural of Serra Malcata

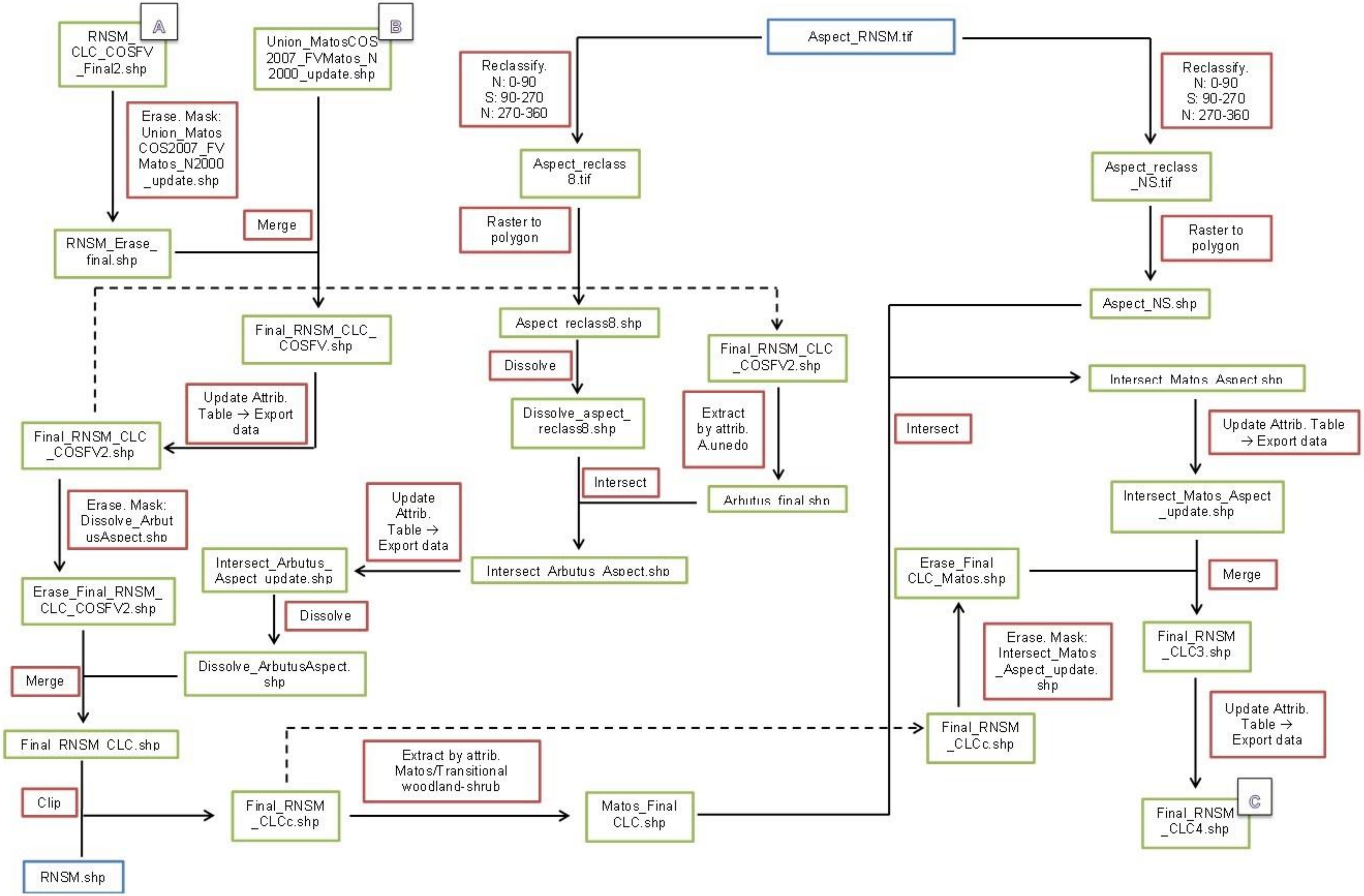


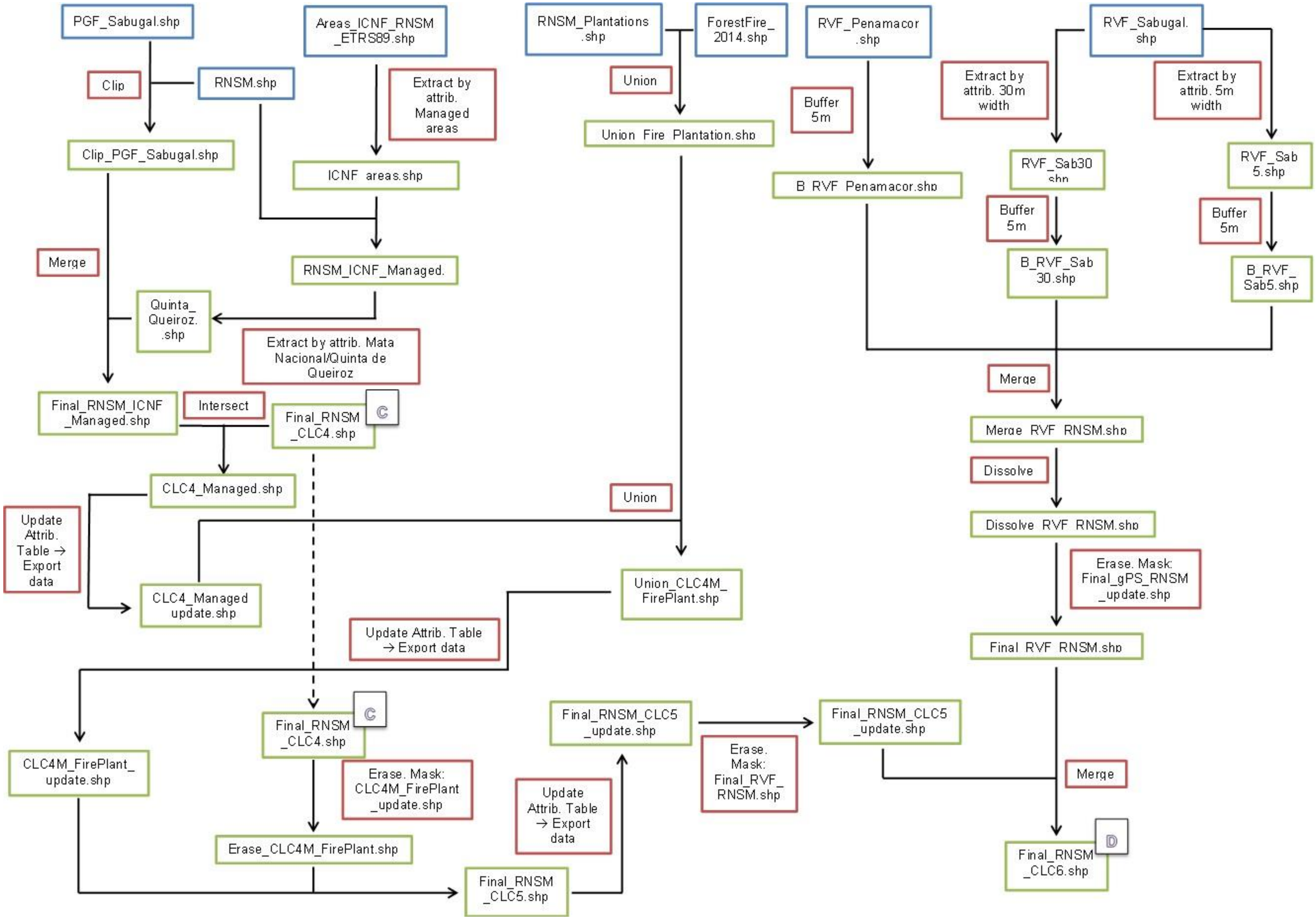
Aspect map of Reserva Natural of Serra Malcata

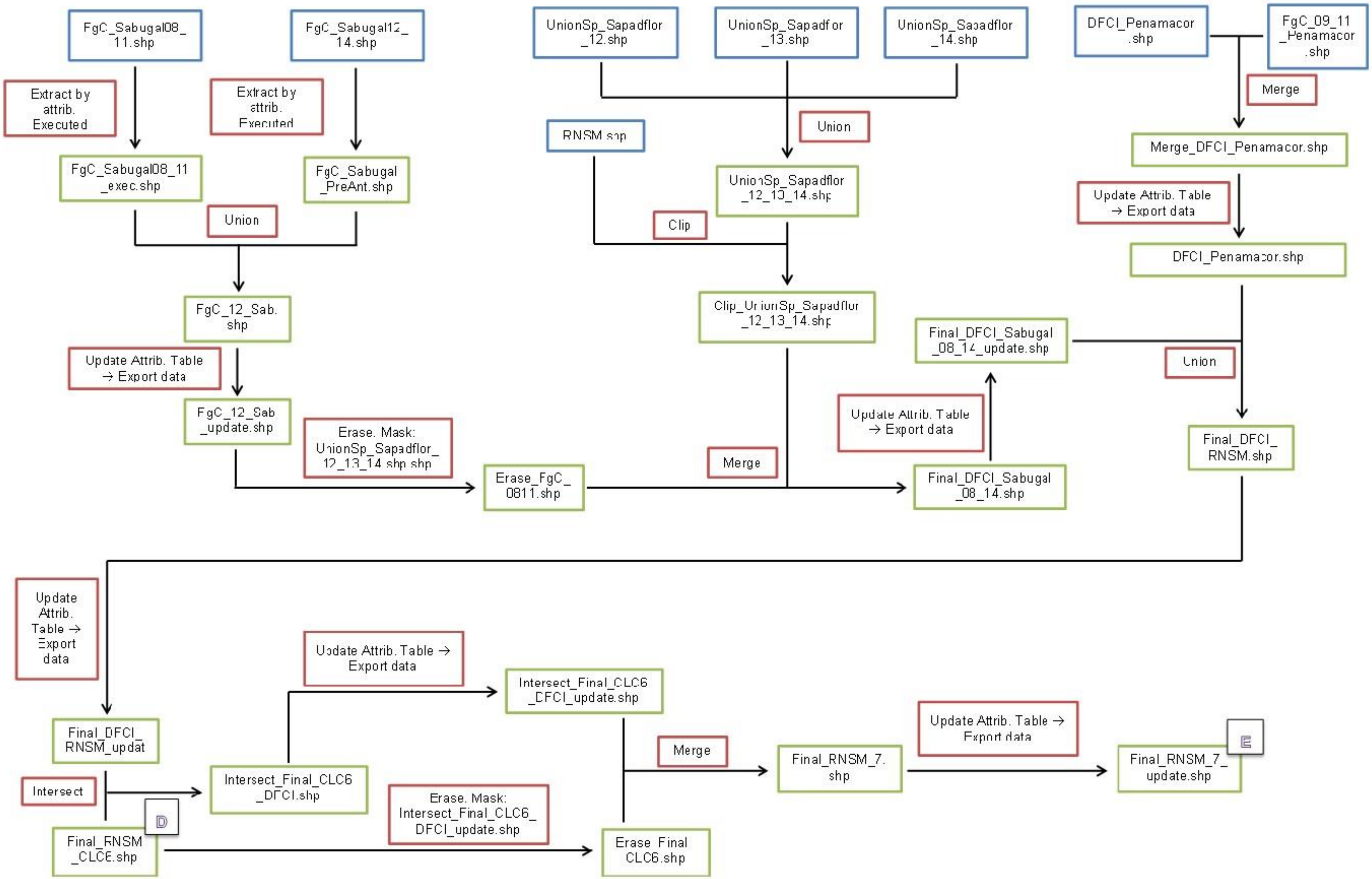


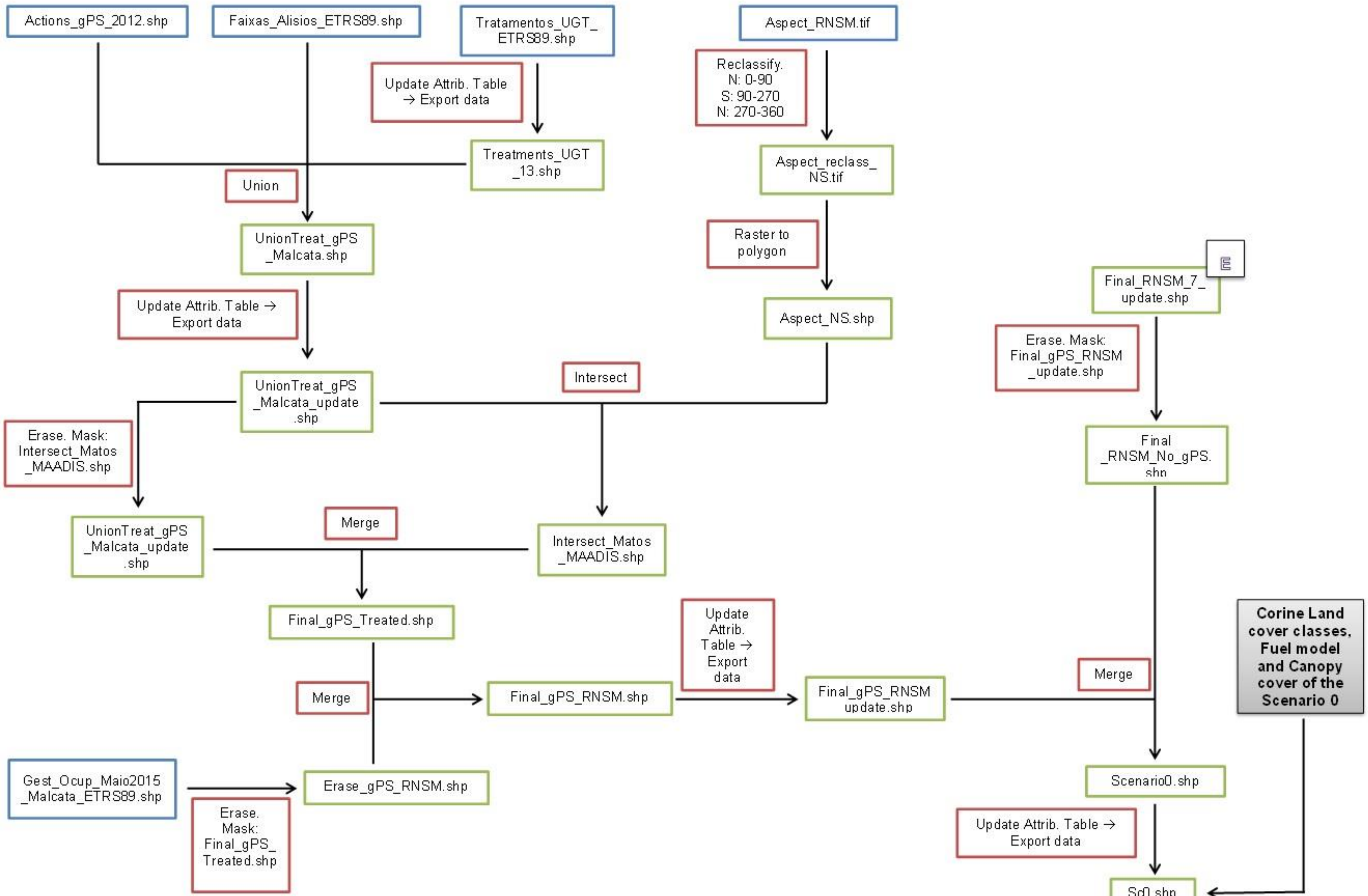
ANNEX II. Flow diagram of the Corine Land Cover for RNSM & Fuel Model & Canopy Cover inputs of RNSM area for Scenario 0



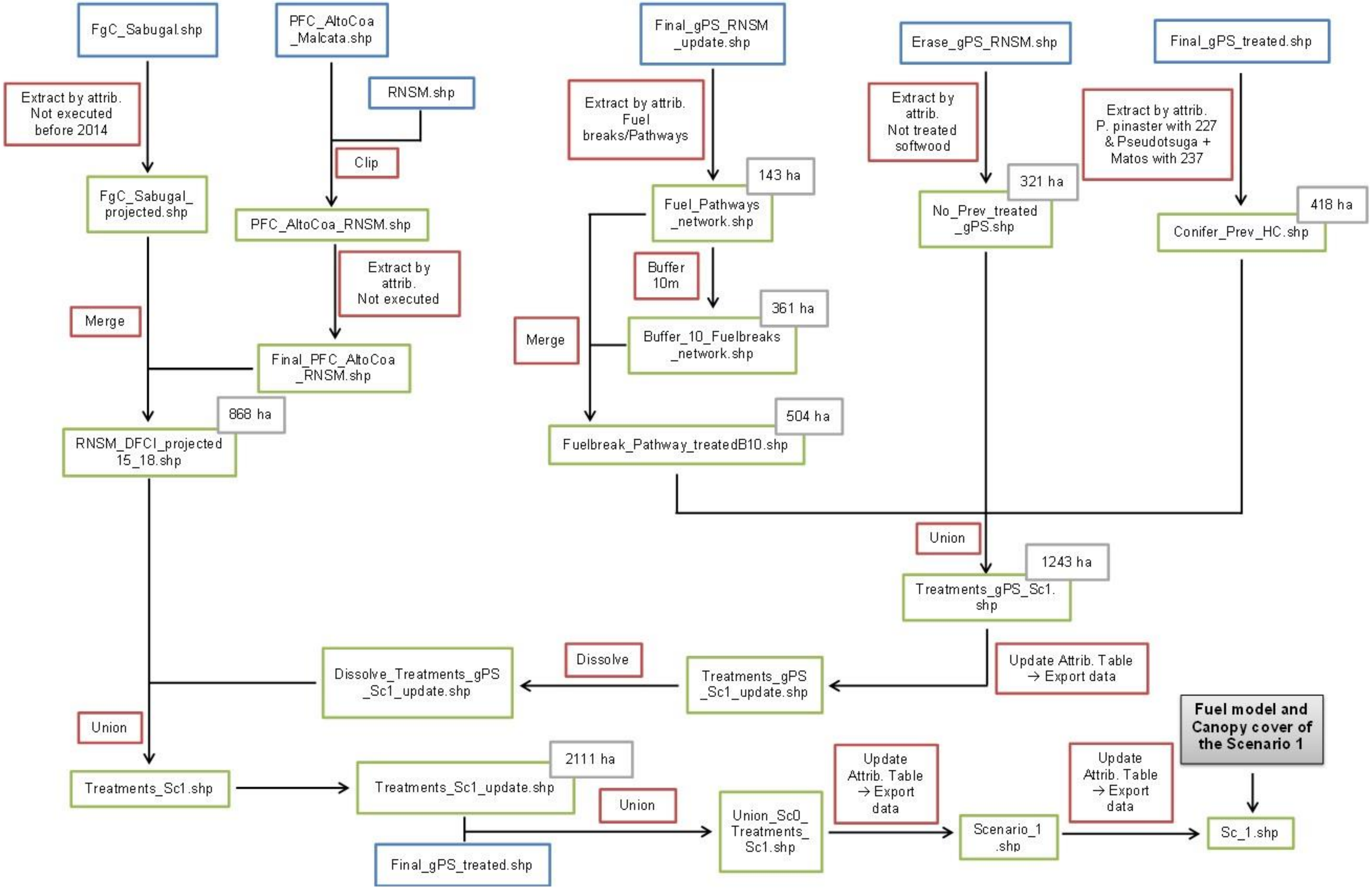

RNSM_CLC_COSFV_Final2.shp
A
Union_MatosCOS2007_FVMatos_N2000_update.shp
B
Aspect_RNSM.tif
Reclassify. N: 0-90 S: 90-270 N: 270-360
Reclassify. N: 0-90 S: 90-270 N: 270-360
Erase. Mask: Union_Matos COS2007_FV Matos_N2000 _update.shp
Aspect_reclass 8.tif
Aspect_reclass _NS.tif
Merge
Raster to polygon
Raster to polygon
RNSM_Erase_final.shp
Aspect_NS.shp
Final_RNSM_CLC_COSFV.shp
Aspect_reclass8.shp
Final_RNSM_CLC_COSFV2.shp
Dissolve
Intersect_Matos_Aspect.shp
Update Attrib. Table → Export data
Dissolve_aspect_reclass8.shp
Extract by attrib. A.unedo
Intersect
Update Attrib. Table → Export data
Final_RNSM_CLC_COSFV2.shp
Intersect
Arbutus_final.shp
Intersect_Matos_Aspect_update.shp
Erase. Mask: Dissolve_ArbutusAspect.shp
Update Attrib. Table → Export data
Intersect_Arbutus_Aspect_update.shp
Intersect_Arbutus_Aspect.shp
Erase_Final CLC_Matos.shp
Merge
Erase_Final_RNSM_CLC_COSFV2.shp
Dissolve
Erase. Mask: Intersect_Matos _Aspect_update. shp
Final_RNSM _CLC3.shp
Merge
Dissolve_ArbutusAspect. shp
Update Attrib. Table → Export data
Final_RNSM_CLC.shp
Final_RNSM _CLCc.shp
Extract by attrib. Matos/Transitional woodland-shrub
Clip
Final_RNSM _CLCc.shp
Matos_Final CLC.shp
Final_RNSM _CLC4.shp
C
RNSM.shp


PGF_Sabugal.shp
Areas_ICNF_RNSM_ETRS89.shp
RNSM_Plantations.shp
ForestFire_2014.shp
RVF_Penamacor.shp
RVF_Sabugal.shp
Clip
RNSM.shp
Extract by attrib. Managed areas
Union
Buffer 5m
Extract by attrib. 30m width
Extract by attrib. 5m width
Clip_PGF_Sabugal.shp
ICNF_areas.shp
Union_Fire_Plantation.shp
B_RVF_Penamacor.shp
RVF_Sab30.shp
RVF_Sab5.shp
Buffer 5m
Buffer 5m
Merge
RNSM_ICNF_Managed.
B_RVF_Sab30.shp
B_RVF_Sab5.shp
Quinta_Queiroz.shp
Extract by attrib. Mata Nacional/Quinta de Queiroz
Merge
Final_RNSM_ICNF_Managed.shp
Intersect
Final_RNSM_CLC4.shp
C
Merge_RVF_RNSM.shp
CLC4_Managed.shp
Dissolve
Union
Update Attrib. Table → Export data
Dissolve_RVF_RNSM.shp
Erase. Mask: Final_gPS_RNSM_update.shp
CLC4_Managed update.shp
Union_CLC4M_FirePlant.shp
Update Attrib. Table → Export data
Final_RVF_RNSM.shp
Final_RNSM_CLC4.shp
C
Final_RNSM_CLC5_update.shp
Final_RNSM_CLC5_update.shp
CLC4M_FirePlant_update.shp
Erase. Mask: CLC4M_FirePlant_update.shp
Erase. Mask: Final_RVF_RNSM.shp
Update Attrib. Table → Export data
Merge
Erase_CLC4M_FirePlant.shp
Final_RNSM_CLC6.shp
D
Final_RNSM_CLC5.shp


FgC_Sabugal08_11.shp
FgC_Sabugal12_14.shp
Extract by attrib. Executed
Extract by attrib. Executed
FgC_Sabugal08_11_exec.shp
FgC_Sabugal_PreAnt.shp
Union
FgC_12_Sab.shp
Update Attrib. Table → Export data
FgC_12_Sab_update.shp
Erase. Mask: UnionSp_Sapadflor_12_13_14.shp.shp
Erase_FgC_0811.shp
UnionSp_Sapadflor_12.shp
UnionSp_Sapadflor_13.shp
UnionSp_Sapadflor_14.shp
Union
RNSM.shp
UnionSp_Sapadflor_12_13_14.shp
Clip
Clip_UnionSp_Sapadflor_12_13_14.shp
Merge
Final_DFCI_Sabugal_08_14.shp
Update Attrib. Table → Export data
Final_DFCI_Sabugal_08_14_update.shp
DFCI_Penamacor.shp
FgC_09_11_Penamacor.shp
Merge
Merge_DFCI_Penamacor.shp
Update Attrib. Table → Export data
DFCI_Penamacor.shp
Union
Final_DFCI_RNSM.shp
Update Attrib. Table → Export data
Final_DFCI_RNSM_updat
Intersect
Final_RNSM_CLC6.shp
Intersect_Final_CLC6_DFCI.shp
Update Attrib. Table → Export data
Intersect_Final_CLC6_DFCI_update.shp
Erase. Mask: Intersect_Final_CLC6_DFCI_update.shp
Erase_Final_CLC6.shp
Merge
Final_RNSM_7.shp
Update Attrib. Table → Export data
Final_RNSM_7_update.shp


Actions_gPS_2012.shp
Faixas_Alisios_ETRS89.shp
Tratamentos_UGT_ ETRS89.shp
Update Attrib. Table → Export data
Treatments_UGT _13.shp
Union
UnionTreat_gPS _Malcata.shp
Update Attrib. Table → Export data
UnionTreat_gPS _Malcata_update .shp
Aspect_RNSM.tif
Reclassify. N: 0-90 S: 90-270 N: 270-360
Aspect_reclass_ NS.tif
Raster to polygon
Aspect_NS.shp
Intersect
Erase. Mask: Intersect_Matos _MAADIS.shp
UnionTreat_gPS _Malcata_update .shp
Merge
Intersect_Matos _MAADIS.shp
Final_gPS_Treated.shp
Merge
Final_gPS_RNSM.shp
Update Attrib. Table → Export data
Final_gPS_RNSM update.shp
Gest_Ocup_Maio2015 _Malcata_ETRS89.shp
Erase. Mask: Final_gPS_ Treated.shp
Erase_gPS_RNSM.shp
Final_RNSM_7_ update.shp
Erase. Mask: Final_gPS_RNSM _update.shp
Final _RNSM_No_gPS. shp
Merge
Corine Land cover classes, Fuel model and Canopy cover of the Scenario 0
Scenario0.shp
Update Attrib. Table → Export data
Sc0.shp

ANNEX III. Flow diagram of the Corine Land Cover for RNSM & Fuel Model & Canopy Cover inputs of RNSM area for Scenario 1



ANNEX IV. Flow diagram of the Corine Land Cover for RNSM & Fuel Model & Canopy Cover inputs of RNSM area for Scenario 2