CONTRIBUTO PARA O PLANEAMENTO DO USO DO
FOGO CONTROLADO NA GESTÃO DE COMBUSTÍVEIS À
ESCALA DA PAISAGEM

Carlos Alberto Rodrigues Loureiro da Silva
Este trabalho foi apresentado na Universidade de Trás-os-Montes e Alto Douro como dissertação para obtenção do grau de Mestre no âmbito do Curso de Mestrado em Instrumentos e Técnicas de Apoio ao Desenvolvimento Rural na referida Universidade.
RESUMO

Um primeiro estudo foi realizado num povoamento de pinheiro bravo (*Pinus pinaster*). Os objectivos foram avaliar em que medida a aplicação de fogo controlado consegue uma redução na continuidade dos combustíveis ao nível da paisagem, e optimizar a sua distribuição espacial e temporal. O software FRAGSTATS foi utilizado para quantificar as mudanças na estrutura e na continuidade da do combustível na paisagem, associado à informação sobre a acumulação de combustível. Cenários alternativos em termos da distribuição espacial das áreas tratadas foram simulados utilizando uma abordagem com base na teoria de percolação. A fim de optimizar o efeito na redução da continuidade do combustível e analisar as configurações espaciais que minimizam a propagação de incêndios catastróficos, foi simulado o comportamento do fogo ao nível da paisagem com o software FARSITE. São propostas algumas recomendações para optimizar o efeito dos tratamentos no espaço e no tempo.

Um projecto de gestão de combustíveis ao nível da paisagem foi executado pelos Serviços Florestais na Serra do Marão, N Portugal. Descreveu-se o plano de tratamentos e usou-se o simulador de comportamento do fogo FARSITE para avaliar os efeitos sobre a propagação e comportamento do fogo na paisagem, em comparação com a situação pré-tratamento. O projecto de gestão de combustíveis foi concebido para uma bacias hidrográfica com 1728 ha, predominantemente ocupada por matos de *Erica* sp. e por jovens plantações de *Pinus nigra*. O tratamento com fogo controlado abrange 11,5% da bacia, criando um padrão de faixas de gestão de combustíveis parcialmente sobrepostas, com larguras de 70 a 120 m. Nas simulações foram utilizados modelos de combustível personalizados e um cenário meteorológico extremo para a situação pré-e pós-tratamento. No pior cenário (ausência de supressão e propagação nas faixas) o tratamento é bem sucedido em retardar propagação do fogo, mas aumenta a extensão da frente de fogo. A velocidade de propagação média e a intensidade da frente de fogo são reduzidas em 36% e 33%. A fração da bacia hidrográfica onde o ataque directo teria sido ineficaz e eficaz, sofreu, respectivamente, uma redução de 41% e um aumento de 88%. As deficiências do projecto são discutidas, especialmente em relação à largura das faixas de gestão e projecções de fogo. Análise do resultado das simulações suporta o efeito positivo do tratamento de combustível na diminuição do potencial de incêndios severos e de grande dimensão.

Palavras-chave: Fogo controlado, dinâmica de combustíveis, fragmentação da paisagem, eficácia da gestão de combustíveis, simulação de incêndios na paisagem, *Pinus pinaster*

ABSTRACT

A first study has been carried in a maritime pine stand (*Pinus pinaster*). The objectives were to assess to what extent the application of prescribed burning achieves a reduction in fuel continuity at the landscape level, and to optimize its spatial and temporal distribution. The FRAGSTATS software was used to quantify changes in the structure and continuity of the overall fuel patch, coupled to information concerning fuel accumulation patterns. Alternative scenarios in terms of the spatial distribution of the burned plots were simulated using a percolation theory approach. In order to optimize the fuel continuity reduction effect of prescribed burning and examine spatial configurations that minimize catastrophic fire spread, fire behavior was simulated at the landscape level with FARSITE software. Some recommendations to optimize the PB effect in space and time are proposed.

A landscape-level fuel management project was implemented by the Forest Service in the Marão mountain range, NW Portugal. We describe the treatment planning and use the FARSITE fire growth simulator to assess its effects on landscape fire propagation and behaviour in comparison with the pre-treatment situation. The fuel management project was conceived for a 1728 ha third order watershed predominantly occupied by *Erica*-dominated shrubland and young *Pinus nigra* plantations. 11.5% of the watershed was treated by prescribed fire creating partially overlapped fuel breaks with widths mostly in the range of 70 to 120 m. Custom fuel models and extreme fire weather were used in the simulations for the pre- and post-treatment situation. In a worst-case scenario (absence of suppression and burnable fuel breaks) the treatment is successful in slowing fire spread but increases the fire front length. Mean rate of spread and fireline intensity are reduced by 36% and 33%. The fraction of the watershed where direct attack would have been respectively ineffective and effective by ground attack suffered a 41% decrease and an 88% increase. The deficiencies of the project are discussed, especially concerning fire break width in relation to spotting. Analysis of the simulation is supportive of a fuel treatment positive effect in diminishing the potential for severe and large-scale fire.

Keywords: Prescribed burning, fuel dynamics, landscape fragmentation, fuel management effectiveness, landscape fire simulation, *Pinus pinaster*
Índice

Lista de símbolos ........................................................................................................ iv
Lista de figuras ......................................................................................................... v
Lista de quadros ...................................................................................................... vi
A. INTRODUÇÃO
1. Enquadramento ................................................................................................. 2
B. PUBLICAÇÕES
2. Prescribed Burning Planning at Landscape Level .............................................. 6
   2.1. Introduction .................................................................................................. 6
   2.2. Planning prescribed burning on the landscape ........................................... 7
      2.2.1 Planning objectives. Fuel management and fire behaviour .................... 7
      2.2.2. Treatments shape and size ................................................................... 8
      2.2.3. Where to place treatments in the landscape ......................................... 11
      2.2.4. How much of the landscape should be treated? Operational and financial resources and treatment return interval ........................................ 12
      2.2.5. Spatial arrangement of fuel treatments ................................................ 13
   2.3 FlamMap simulator ..................................................................................... 14
   2.4 Final remarks .............................................................................................. 15
3. Spatial simulation of fire spread: two different approaches applied to Tapada de Mafra, CW Portugal .................................................................................. 16
   3.1. Introduction ................................................................................................ 16
      3.1.1. Study area......................................................................................... 16
      3.1.2. Objectives ......................................................................................... 16
   3.2. Fire simulators ........................................................................................... 16
      3.2.1. Landlord – Spatial modelling system (version 1.2) .................................. 16
      The ModMED landscape fire modelling (Heathfield and Rego 1997) ............ 17
      Factors that affect contagion probability ................................................... 18
      3.2.2. FARSITE - Fire Area Simulator (Finney 1998) ...................................... 18
   3.3. Methodology .............................................................................................. 20
      3.3.1. Applying the ModMed fire model to some historical fire data from Tapada de Mafra .............................................................. 20
      The simulation data and their preparation ................................................... 20
      Preparing the elevation grid map ................................................................. 22
      Preparing the land use grid map ................................................................. 22
      Estimating the fuel horizontal continuity .................................................... 23
      Estimating the fuel moisture using riparian zones ....................................... 24
      Estimating the fuel moisture using aspect .................................................. 24
      Winds .......................................................................................................... 25
      The damage maps ...................................................................................... 25
      3.3.2. Applying FARSITE using custom fuel models developed for Tapada de Mafra ...... 26
      The simulation data and their preparation ................................................... 26
      Landscape file ............................................................................................ 27
      Weather, wind and fuel files ....................................................................... 27
   3.4. Results ....................................................................................................... 28
      3.4.1. Landlord fire simulation .................................................................... 28
      3.4.2. FARSITE fire simulation ................................................................... 29
      Output maps ............................................................................................... 30
   3.5. Conclusions ............................................................................................... 31
4. Optimizing prescribed burning to reduce wildfire propagation at the landscape scale ...... 32
   4.1 Introduction ................................................................................................ 32
   4.2 Methods ..................................................................................................... 33
   4.3. Results ..................................................................................................... 35
      4.3.1. Analysis of the prescribed fire effect in the 1993-1999 period ............... 35
      4.3.1.1. Conclusion .................................................................................. 37
      4.3.2. Proposal of improved prescribed fire application in study area .......... 38
4.4. Fire behaviour simulation using FARSITE ........................................................ 39
4.5. Final Recommendations ............................................................................ 40
5. A simulation-based test of landscape fuel management alternatives in the Marão range of northern Portugal............................................................. 41
  5.1. Introduction .......................................................................................... 41
  5.2. The fuel treatment project ...................................................................... 42
  5.3. Objectives ........................................................................................... 43
  5.4. Methods ............................................................................................. 43
  5. Results and Discussion............................................................................... 46
    5.1. FARSITE simulation ........................................................................... 46
    5.2. FlamMap simulations ......................................................................... 50
  5.6. Conclusion ........................................................................................... 53
  5.7. Final considerations .............................................................................. 54
C. CONCLUSÕES
  6. Considerações finais .................................................................................. 57
Bibliografia ...................................................................................................... 62
Agradecimentos ............................................................................................... 66
Lista de símbolos

ASCII - American Standard Code for Information Interchange
DEM - Digital Elevation Model
EUA - Estados Unidos da América
FLI - Fire Line Intensity
GIS - Geographic Information Systems
HC - Horizontal Continuity
LPI - Largest Patch Index
MIP - Mixed Integer Programming
MPS - Mean Patch Size
MTT - Minimum Travel Time
NFFL - Northern Forest Fire Laboratory
PB - Prescribed Burning
ROS - Rate of Spread
SIG - Sistemas de Informação Geográfica
TOA - Time of Arrival
TOM - Treatment Optimization Model
USA - United States of America
Lista de figuras

Figure 3-1. Raster landscape input layers required from the GIS for FARSITE simulation (Finney 1998). .................................................................................................... 19
Figure 3-2. Plan of steps used to run a FARSITE simulation ................................................ 20
Figure 3-3. Grid specification and grid map of Tapada de Mafra area. ........................................ 21
Figure 3-4. Digital elevation model (DEM) map of Tapada de Mafra area. ............................... 22
Figure 3-5. Land use map of Tapada de Mafra area. ............................................................... 23
Figure 3-6. Fuel horizontal continuity map of Tapada de Mafra area. ........................................ 23
Figure 3-7. Water lines map and fuel moisture estimation. ..................................................... 24
Figure 3-8. Fuel moisture adjustment map using aspect. ....................................................... 24
Figure 3-9. Burnt area of the 1975 wildfire. ......................................................................... 25
Figure 3-10. Fuel models map of Tapada de Mafra. .............................................................. 27
Figure 3-11. Example of an output map of the simulation. ..................................................... 28
Figure 3-12. Fuel horizontal continuity (HC) model graphic and fuel HC map for Tapada de Mafra .......................................................... 29
Figure 3-13. Screen shot of FARSITE simulation result. ..................................................... 29
Figure 3-14. Graphic evolution of Burned area versus Time, during the simulation................. 30
Figure 3-15. Fireline intensity map, resulting from FARSITE simulation. ............................... 30
Figure 3-16. Rate of spread map, resulting from FARSITE simulation. ................................... 31
Figure 4-1. Distribution of PB areas by season in Perímetro Florestal do Entre-Vez-e-Coura..... 32
Figure 4-2. Prescribed burning active area and LPI (1993-1999). ............................................ 36
Figure 4-3. Prescribed burning active area and MPS (1993-1999). ......................................... 37
Figure 4-4. Hypothetical modification of the spatial location of two plots in 1999. .................... 37
Figure 4-5. Prescribed burning active area and LPI for the two scenarios. ............................... 38
Figure 4-6. Prescribed burning active area and MPS for the two scenarios. .............................. 38
Figure 4-7. Percentage of burnt area by fireline intensity, in the two FARSITE simulations ... 40
Figure 5-1. Location of the prescribed fire units (left) and fuel model map (right). For the meaning of fuel model numbers see tables 1 and 2. Model 15 is NFFL 5 modified to represent Cytisus shrubland ................................................................. 42
Figure 5-2. Proposal for fuel treatment location from the Treatment Optimization Model (TOM), respectively for SE wind (left) and upslope wind (right). ...................................................... 45
Figure 5-3. Fireline length and cumulative burned area in the watershed, before and after the fuel treatment, and as a function of time elapsed since the wildfire enters the watershed. .................................................................................... 47
Figure 5-4. Fire front time of arrival before (left) and after (right) the fuel treatment. ...............47
Figure 5-5. Classification of fire behaviour before (left) and after (right) the fuel treatment: rate of spread (top, m min-1) and fireline intensity (bottom, kW m-1). ................................. 48
Figure 5-6. Watershed distribution (%) by classes of fire spread rate (right, m min-1) and fireline intensity (left, kW m-1), before and after the fuel treatment. 49
Figure 5-7. Cumulative burned area in the watershed, before and after the fuel treatment, and as a function of time elapsed since the wildfire enters the watershed. Left - SE wind; Right - upslope wind. ..................................................................................... 47
Figure 5-8. Watershed distribution (%) by classes of fire spread rate (m min-1), without treatment and after the two proposed fuel treatments for the SE wind (left) and upslope wind (right) scenarios. .............................. 50
Figure 5-9. Watershed distribution (%) by classes of fireline intensity (kW m-1), without treatment and after the two proposed fuel treatments for the SE wind (left) and upslope wind (right) scenarios. .................................................................. 51
Figure 5-10. Classification of rate of spread (m min-1) before and after the fuel treatments for the SE wind (top) and upslope wind (bottom) scenarios. ............................. 51
Figure 5-11. Classification of fireline intensity (kW m-1) before and after the fuel treatments for the SE wind (top) and upslope wind (bottom) scenarios. ............................. 52
Figure 6-1. Exemplificação do efeito do tratamento em parcelas adjacentes em anos consecutivos. .................................................................................. 59
Table 3-1. Custom fuel models parameters (metric units) used in the FARSITE simulations........ 26
Table 4-1. Variation in the active prescribed fire area and in the LPI and MPS indexes, for the perimeter and global areas............................................................. 36
Table 4-2. Custom fuel models parameters (metric units) used in the FARSITE simulations.... 39
Table 5-1. Custom fuel models for shrubland in the study area. ........................................ 44
Table 5-2. Fuel models distribution and patch characteristics in the simulation area for the pretreatment. ...................................................................................... 44
Table 5-3. Landscape scenarios tested in the simulations............................................... 45
Tabela 6-1. Esquema de delineamento para planeamento estratégico de gestão de combustíveis com recurso a simuladores de comportamento do fogo.............................. 61
A. INTRODUÇÃO
1. Enquadramento

Esta tese de mestrado tem por base vários trabalhos sobre a temática do fogo controlado e do seu planeamento à escala da paisagem desenvolvidos no Grupo de fogos da UTAD entre anos de 2000 e 2010, no âmbito de diversos projectos de investigação. Os capítulos seguem a sequência cronológica das publicações, relativas à aplicação do uso dos simuladores de comportamento do fogo para análise do efeito de tratamentos com fogo controlado em espaços florestais, para determinação das alterações no potencial de propagação de incêndios e comportamento do fogo associado.

No capítulo 2 faz-se uma revisão bibliográfica sobre o planeamento espacial (ou seja, ao nível da paisagem) de tratamentos de combustíveis, com especial ênfase no recurso ao fogo controlado. Este capítulo foi originalmente redigido como parte integrante do Deliverable 5.4.1\(^1\) do Projecto Fire Paradox. Os objectivos do planeamento são quase exclusivamente orientados para a redução do perigo de incêndio. Modelos de comportamento do fogo e simuladores de propagação espacial do fogo são uma componente essencial no processo de decisão. Permitem uma análise à escala da paisagem, para determinar os locais mais eficazes e arranjo espacial dos tratamentos, com base na topografia, e cartografia e características dos combustíveis.

Diferenças estruturais da propriedade florestal e dos objectivos da gestão florestal são evidentes entre as regiões mediterrâneas do continente europeu e os constrangimentos que se impõem à gestão de combustíveis em países como EUA e Austrália, onde esta temática tem sido mais investigada. Considerações de ordem prática (recursos disponíveis, acessibilidade, e as restrições ambientais e sociais) são componentes necessárias no processo de tomada de decisão. Estas restrições podem interferir com os resultados dos modelos e simulações, ao ponto de serem mais relevantes na decisão final.

A expansão do uso dos Sistemas de Informação Geográfica (SIG) e sua aplicação à análise de risco de incêndio florestal levaram à necessidade do uso de simuladores para o comportamento do fogo que produzem resultados gráficos (mapas), para posterior análise e incorporação na cartografia de perigo de incêndio, e como ferramentas para apoiar os planos gestão florestal, na prevenção e defesa da floresta contra incêndios.

A. INTRODUÇÃO

O capítulo 3 tem por base uma primeira aproximação à utilização de programas de simulação de propagação do fogo, que visa comparar duas abordagens diferentes para a simulação de incêndio. Uma abordagem muito simples, desenvolvida no âmbito do projecto europeu ModMed, e funcionando como um módulo do software Landlord - spatial modeling system v1.2. O outro, FARSITE - Fire Area Simulator, com mérito confirmado pelo amplo uso em diferentes países. Estas duas abordagens foram aplicadas à área de estudo da Tapada de Mafra, beneficiando da existência da necessária informação de base, recolhida no âmbito do projecto ModMed.


Os objectivos foram avaliar em que medida a aplicação de fogo controlado em parcelas dispersas se traduz numa redução na continuidade dos combustíveis ao nível da paisagem, e optmizar a sua distribuição espacial e temporal. O software FRAGSTATS foi utilizado para quantificar as mudanças na estrutura e na continuidade do combustível, em associação com informação sobre os padrões de acumulação de combustível com o tempo.

Cenários alternativos, em termos da distribuição espacial das áreas tratadas, foram simulados, utilizando uma abordagem baseada na percolação. Procurou-se optmizar o efeito do fogo controlado na redução na continuidade da carga de combustível, e analisar as configurações espaciais que minimizam a propagação de incêndios catastróficos. Para este efeito foi simulado o comportamento do fogo ao nível da paisagem com o software FARSITE. Algumas recomendações para optimizar o efeito do fogo controlado no espaço e no tempo são propostas.

No capítulo 5 examina-se um plano de tratamento de combustíveis ao nível da paisagem, implementado na área da Serra do Marão, norte de Portugal. Este plano representou em 2005 uma alteração na aplicação do fogo controlado para gestão de combustíveis. Foi o

---

3 ModMED – Modelling Vegetation Dynamics and Degradation in Mediterranean Ecosystems. European Commission DG-XII  
A. INTRODUÇÃO

primeiro executado numa perspectiva de planeamento à escala da paisagem. O efeito do
tratamento sobre o potencial de incêndios é avaliado com o software FARSITE, em comparação
com o cenário de pré-tratamento de combustível.

Uma alternativa ao plano de gestão implementado foi obtida utilizando o software
FlamMap, através da ferramenta Treatment Optimization Model (TOM). Em seguida, usou-se
novamente o FlamMap para comparar a eficácia do tratamento efectuado no terreno com a
proposta de optimização para dois cenários distintos de simulação fogo. Um cenário de
propagação dominada pelo vento, usando mapas de vento produzidos no software WindNinja, e
um segundo cenário com a propagação dominada pela topografia. O efeito dos tratamentos nas
características do comportamento do fogo foi obtido a partir dos resultados das simulações, e
comparado para os dois cenários.
B. PUBLICAÇÕES
2 Prescribed Burning Planning at Landscape Level

2.1. Introduction

Fire is an important part of Mediterranean ecosystems and forest fires have always been present in southern Europe rural areas. However, in the past, fire expression in the landscape was related with land use and space occupation, in a time when humans were substantially more present in rural areas. Such influence constrained fire size, since the intense use of forests and their resources was effective at increasing spatial heterogeneity and decreasing flammability, hence decreasing landscape vulnerability to fire.

Demographical and land use changes over the past decades have led to dramatic changes in the fire regime, both nationally and throughout Europe, especially in the Mediterranean basin. New challenges arise in regards to forest and fuel management, which are constrained by scarce human resources and decreasing funding. It doesn’t help that the political response to the wildfire problem privileges investment in fire suppression, which paradoxically can contribute to larger and more severe fires in the future (Fernandes 2008).

The use of prescribed fire as a fuel management technique in Europe dates back from the 1970’s, and was inspired in the United States practice. The first extensive prescribed fire management program was launched in Portugal. However, the traditional use of fire in wildland management is old and deeply rooted in rural communities throughout the Mediterranean, especially to renew and maintain rangelands in mountain areas.

Diverse studies in the western Mediterranean have been carried out since the 1980’s to characterize the environmental effects of prescribed burning. The burning conditions commensurate with the achievement of management objectives have been defined, and the importance and appropriateness of prescribed burning to manage European Mediterranean ecosystems is now recognized.

Prescribed burning planning is carried out at two different scales. At the plot/stand level, is focused mainly on the prescription that leads to specific treatment effects. The other, at the landscape scale, where planning should address the strategical location of treatments to protect the greatest value areas from the effects of catastrophic wildfires (Hunter et al. 2007), limiting wildfire spread and providing more opportunities to effective fire suppression. Finney and Cohen (2003) suggest to differentiate wildland-urban-interface environments, where planning should take into account the combination of built structures and vegetation areas.

If for the plot/stand level of planning there is little doubt about its design and efficiency, only recently has spatial planning been the subject of analysis and proposals for
optimization, especially for fuel management and fire hazard mitigation. Prescribed burning planning at the landscape scale implies several questions related with burn objectives and fire use restrictions. Other constraints to consider are common with fuel management planning in general, regardless of the treatment used.

Several issues directly restrain the applicability of prescribed fire (Fernandes and Botelho 2003). There are restrictions on the use of fire on a large scale in relation to its effect on air quality and local residents health (Agee and Skinner 2005), or on the use of fire in wildland-urban interface areas, which offers additional difficulties due to increased complexity of social and technical issues, and where most of the effort focuses on the need for planning and coordination prior to the burn operation (Miller and Wade 2003). This same complexity is apparent in the Mediterranean basin, due to patterns in land use type and objective, land ownership, and human occupation. The demand for skilled personnel and the necessity to respect meteorological windows of opportunity and ecological restrictions, as well as a tighter legal framework, further increase the limitations in comparison with alternative fuel treatments.

2.2. Planning prescribed burning on the landscape

2.2.1 Planning objectives. Fuel management and fire behaviour

The continual accumulation of biomass, that fuels wildfires, points to the need of developing fuel management strategies at the landscape level which are effective at decreasing the size and severity of wildfires (Weatherspoon and Skinner 1996). In a country like USA the fuel build-up problem is mainly related with a fire suppression policy, where the role of fire as an ecosystem process and “manager” has been negated. Concurrent favourable weather conditions lead to an increase in the area burned by high-severity fires (Weatherspoon and Skinner 1996). Fire suppression policies are also in place in Europe. However, the major cause for the high levels of biomass accumulation is related with agricultural land abandonment and the absence or reduced intensity of forest management.

The purpose of fuel management is to modify the behaviour of a future wildfire, by decreasing fuel load and changing vegetation structure. The expected changes in fire behaviour are decreases in rate of spread, fire intensity and crown fire potential. A meaningful change in wildfire behaviour, i.e., a change that will benefit fire suppression, implies that the treatments are effective both locally and in the overall landscape. However, treatment of the entire area is not feasible and its extent is limited by economic, structural, physiographic and ecological constraints. Fuel management needs to be consistent with other management objectives, which can be complementary to wildfire prevention, such as rangeland management, control of pests and diseases and ecosystem sustainability (Hunter et al. 2007, Weatherspoon and Skinner 1996).
The best possible solution for protection against wildfires may not be feasible due to impacts on wildlife, watersheds, or scenic quality objectives (Gercke and Stewart 2006).

Planning should be carried out in the long term, in a sustainable way in order to maintain treatments efficacy over time (Hunter et al. 2007), and in this context it is important to know the period of treatment effectiveness in changing fire behaviour, i.e., which is the time required to recover to a hazardous condition. Treatments should start in the most logical, effective and economically efficient places (Weatherspoon and Skinner 1996). We should consider the implementation of the treatment areas in the landscape, its geometry and the relative position of treatment units. The strategic location of treatments has to maximize their effect in fire behaviour, allowing safe fire fighting and, in some favourable situations, self-containing wildfires.

2.2.2. Treatments shape and size

Two general strategies for landscape-scale fuel treatment can be considered: fire-breaks and fuel-breaks with the main objective of stopping fire spread, or area-wide treatments that form a mosaic of scattered treatments where fire behaviour is modified (Finney 2001). Longitudinal, long and narrow plots that are placed perpendicularly to the main direction of fire spread are the most common spatial strategy of fuel treatment. Traditionally, the implementation of fuel management areas follows this linear pattern of fuel-break, designed to limit wildfire growth, but also as anchor points for indirect attack actions or prescribed burning in neighbouring areas (Agee et al. 2000). This is the tradition in European countries of the Mediterranean, such as Portugal, France and Spain (e.g. Rigolot 2002a), or in some USA regions (Agee et al. 2000), with variation between countries. In Australia, where the areas treated by prescribed fire are typically larger, area-wide treatments are prevalent and have been shown to be effective in decreasing the incidence of large wildfires (Boer et al. 2009).

The aim of each treatment unit is not to stop a fire spreading, but reinforce fire suppression actions (defensible locations) and thus reduce the size of the fire, helping the safe use of indirect attack techniques, including back-fire, but having little effect on fire behaviour and severity outside the treated area (Agee et al. 2000, Finney 2001).

An assessment of fuel-break effectiveness in southern France (Lambert et al. 1999) identified some factors favourable to fire fighting success, namely the quality of the access (location, width and conservation status), fire-fighting resources available on site and synergy between ground and air resources. The following negative factors are mentioned: detection delay (at initial attack level); limited access; herbaceous fuel load (implying faster fires); and the existence of fine fuel pockets, which favour spotting. Therefore, fuel-breaks should be
implemented with the support of roads or tracks, allowing access by fire suppression resources, and regular treatment of fuels.

Duguy et al. (2007) have analyzed the effect of different alternatives for implementing a fuel-break network, suggesting that these structures are effective in reducing wildfire size, but do not reduce the rate of spread or intensity of the fire front. Fuel-breaks by themselves are only successful in slowing the progression of the fire (Finney and Cohen 2003) and significant loss of value may occur within a block bounded by a treated strip only (Agee et al. 2000).

Fuel-breaks can be viewed as the starting point for landscape-level fuel management. Subsequent and more extensive treatments will gradually decrease the fire damage potential within the treated areas (Agee et al. 2000). According to the same authors, a network of connected fuel-breaks is complex. A wildfire will more likely find a fuel-break segment if it’s planning took into account factors such as the potential for ignition and the values at risk. Otherwise, if the pattern of firing events is random and values are regularly or uniformly distributed on the landscape, an approach based on a network of fuel-breaks is always preferable.

Fuel-break features (Finney 2001):

1) Established to help contain fires.
2) Reinforce defensible locations determined prior to fire occurrence.
3) Facilitate indirect suppression tactics, including backfiring.
4) Reduce fire size.
5) Have little effect on fire behaviour or severity outside the treatment area.
6) Burnout operations may lead to larger wildfires and larger areas burned severely.

On the other hand, fuels management planning can result in treatment units spread over the landscape in strategic locations to maximize the benefits gained from changes in fire behaviour (Finney 2001, Parisien 2007). Finney (2001) suggests a pattern for treatments distribution where the treated units overlap in the prevailing direction of fire spread. This pattern is expected to generate fragmentation of extreme fire effects, as the fire front is fragmented by the treatment units.
Partial overlap treatment features (Finney 2001)

1) Treatment unit size is unimportant. Only the relative dimensions of the pattern affect fire spread rate through the pattern. The effect is related with distance between plots and the extent of overlap.

2) The distance between units in the heading direction must be smaller than the wildfire width.

3) Fire spread rate inside the treated area must be slower than in the untreated landscape.

4) A lower percentage of the total area requires treatment as treatments become more effective.

The location and purpose of prescribed burning treatments must decide the units optimal shape. Prescribed burning productivity depends on the area treated per unit of time, which is directly proportional to the ignition line length. The use of anchor points based on existing structures (such as tracks, roads...) can decide the shape of units, optimizing resources and avoiding construction of containment lines.

Spot fires are one of the main concerns in defining treatment size. However, site physiography and type of vegetation can constrain and even determine the optimal size of the treatment units. When the treatments seek to contain a wildfire (as in fire-breaks), their width is often determined by empirical rules or by local experience and dozer size (Davison 1988). There are no default values for fuel and fire break widths. Earlier references (1960 and 1970’s) in the U.S.A. indicate values ranging from 65 to 300 meters (references in Agee et al. 2000). However these widths can be smaller, like in fire-breaks in Australian grassland (2-5 t.ha⁻¹ and 0.15 to 0.55 m height) which range from 5 to 15 m (Davison 1988), based on a model for the probability of fire break breach based on fire intensity, the presence of trees within 20 m firebreak width (Wilson 1988). When implementing a fuel-break network, the size of the different sections may be variable, with subdivisions closer to the most remote, and would function primarily as anchor points for the use of prescribed fire (Agee et al. 2000). In France, expert opinion identified fuel-break width, shrub volume and tree cover as the most discriminating criteria to assess fuel-break effectiveness (Rigolot 2002a). Finney (2007) indicates a treatment units range from 800 to 2500 m, or 65 to 390 ha.

Flexibility in treatment size is important when planning for different landscapes, topography, ecology or constraints. When treatments follow a pattern of dispersed units that overlap partially, the size of the treatment is theoretically independent of scale, i.e., the effect of treatment size is only related with distance between plots and the extent of overlap, which must be less than the fire front width (Finney 2001).
2.2.3. Where to place treatments in the landscape

The distribution pattern (topological and spatial) of treatment plots in the landscape is a major factor to consider when optimizing treatment location, to maximize the effect on fire behaviour and fire hazard reduction (Finney 2001, Noonan 2003, Hunter et al. 2007). Treatment location is usually based on ecological objectives, convenience, cost, ownership or accessibility (Finney 2001). Fuel-breaks are usually located where indirect attack tactics are applied, such as along ridges and roads along valley or slopes (Agee et al. 2000).

The choice of treatment units based on topographic attributes and watershed area, and the use of terrain features such as water lines and ridges to delineate areas of treatment is consistent with the natural boundaries of wildfires (Mislivets 2003, Taylor and Skinner 2003). Duguy et al. (2007) suggest that wildfire spread is reduced by increasing the connectivity between dense forest patches with low fuel load, and promoting patches with more complex shape. Such complexity in burned plots shape is often find in Portugal where fire is traditionally used in range management, and where fire self-extinguishes due to changes in weather conditions or fuels.

Fragmentation of hazardous fuel areas within lower fuel load areas or less flammable vegetation types can be an effective method to reduce the size and intensity of fires, promote biodiversity and landscape resilience to fire (Burrows and van Didden 1991, Brockett et al. 2001, Duguy et al. 2007)

If operational and financial resources allow maintaining in a treated condition 30-40% of the landscape then the spatial pattern of treatment is unimportant, and the difference between randomly distributed treatments and an optimized spatial distribution of treatments is not significant (Finney 2007).

Some studies model fire growth under different treatment scenarios to determine the optimum location of treatments (Finney 2001, Agee et al. 2000). Finney (2007) proposes an algorithm to optimize the location of fuel treatment units to prevent the spread of large fires. The method requires two spatial data sets:

1) The current fuel situation;

2) The potential fuel situation, after treatment in an area previously identified as possible to treat.

The difference in fire spread across the landscape between these two scenarios, under identical weather conditions, indicates where the treatments are effective in slowing fire growth.
2.2.4. How much of the landscape should be treated? Operational and financial resources and treatment return interval

To decide the burning rotation period, three factors must be weighed (Keeley 2002):

1) The competence of skilled personnel to safely maintain fire within the planned boundaries;

2) Vegetation likelihood to ignite and sustain fire spread.

3) And finally, for how long will the treatment persist, i.e., for how long it will be effective in reducing fire danger.

Fire behaviour in the landscape changes above a fuel type composition threshold (Bevers et al. 2004, Duguy et al. 2007). In randomly allocated treatments, effectiveness is related to the treated area fraction (Finney 2003, Bevers et al. 2004) and aggregation (clusters) of treated units. The more aggregated the treatments are, the largest proportion of the area must be treated (Bevers et al. 2004).

Fire severity in treated areas increases with time since treatment (e.g. Fernandes et al. 2004). However, other factors can affect fire severity, e.g. Finney et al. (2005) report decreases with treated plot size and number of previous prescribed fires. Prescribed burning is more effective in reducing surface fine fuel (Lambert et al. 1999), and a seasonal distribution allows a variety of burning conditions that reflects in the size and intensity of prescribed fires, and in the spatial and temporal distribution of this variation (Brockett et al. 2001). Consequently, the season of burn can have implications on the treatment return interval.

Maintenance treatments frequency varies with region and vegetation type and can be determined from historical fire regimes or from the rate of fuel accumulation (Hunter et al. 2007). In southern France, efficient fuel-breaks require treatment intervals of 3 to 4 years, as judged from shrub volume (Rigolot 2002a). Several examples of treatments longevity indicate that prescribed burning reduces the severity of wildfire for 2 to 25 years after treatment (Hunter et al. 2007).

The annual treatment rate, or maintenance, should be high enough to compensate or overcome the temporal decrease in effectiveness. Finney (2007) proposes that the annual treated area fraction should be $1/n$, where $n$ is fuel recovery time (years). E.g., if $n=4$ years, then the area treated every year should be 0.25 of the total percentage of treated landscape. If the total percentage of treated landscape is 20% (which roughly cuts the area burned to half if the treatments are strategically placed), then 5% should be treated annually. Note that if the treatment pattern is random then the treatment effort would have to double in order to achieve the same effect (Finney 2007).
2.2.5. Spatial arrangement of fuel treatments

Some authors have studied the topic of fuel treatment planning on the landscape, suggesting different methods to optimize the effect of treatments. Normally the process of identifying priority areas for treatment is based on a multiple criteria weighted analysis, and using GIS analysis for criteria selection planning.

Keifer et al (2000) propose a model based on GIS analysis, incorporating ecological role of fire in fire management planning, together with fire risk and hazard. The process includes information about vegetation, fire return interval and fire perimeters from historical records. The result is an index that ranks potential areas for treatment based on the need to restore fire disturbance to its historical range, and allows setting treatment priorities.

Hiers et al (2003) also propose a process for identifying priority areas for the use of prescribed burning, on the basis of key conservation criteria and landscape scale management objectives. The model incorporates the experience of managers and specialists that identify and rank criteria according to the burn priorities. The ranking is dynamic and adjustable to the treatment units limits. The criteria used include time since last fire, site quality, time since treatment for ecosystem restoration and land use classification. Through the use of a GIS, the criteria are weighted according to their relative contributions, leading to a global prioritization of landscape scale burning.

The methodology of MacGregor et al. (2003) to develop fuel management projects involves a set of design decisions, aimed to a broad range of objectives, outlined as evaluation criterion. These criteria may include environmental, economic (including cost), social and risk-related factors. The optimal design is the one that best reflects the alternative value (trade-off value) of that option, coupled with the relative weight or priority assigned to the criterion. This assessment can include a variety of purposes including: a) what is the potential advantage of one plan over another, b) the extent to which a set of plans covers all the objectives, c) where, within the objectives, there may be need to develop new plans. The fuel management program is considered as a portfolio of plans, each rated in terms of benefits and risks.

For Bevers et al (2004) the objective is to create fuel-breaks in the landscape, from a pattern of spatially correlated random treatments. From a map of the treatment area, divided into a grid of cells that represent potential treatment sites, the cells to be treated are randomly selected, using an algorithm that provides, optionally, a greater degree of aggregation of random treatments. However this means that a larger number of randomly treated grid cells are probably needed than if the locations of treatments were chosen strategically.

Wei et al (2008) proposes a mixed integer programming (MIP) for locating fuel treatments on the landscape, based on spatial information of ignition risk, conditional probability of fire spread (between raster cells), fire intensity and values at risk. The
particularity of the model is that fuel treatment locations are not selected based on location and behaviour of specific fires, but fire hazard is assumed to be cumulative over the landscape, along the direction of maximum spread (wind direction). From this assumption the model locates where the treatments are more effective in reducing the fire hazard accumulation. The available budget constrains the amount of treated area.

2.3 FlamMap simulator

Some of the planning strategies consider the identification of higher-risk areas or where the probability of fire is higher. The identification of these areas defines critical candidate areas for treatment and also treatment priorities. Expansion to wider areas in the landscape can subsequently take place from the priority areas.

FlamMap (Finney 2006) is a software that simulates fire behaviour in the landscape and a reference in fire hazard classification and mapping. It can be used to identify the areas where fire hazard is greatest, to support decision, and for validation and optimization. FlamMap includes a module that proposes the best locations for fuel treatments with the goal to stop the spread of large forest fires. It also provides information on: 1) minimum travel time; 2) major fire travel routes; 3) opportunity for treatments; 4) percentage of land area to be treated.

The Treatment Optimization Model used in FlamMap proposes area-wide treatments (or a pattern of dispersed treatments), supported on treatment units topology to reduce the spread and intensity of fire. Its main features are:

1) Fire behaviour and effects are modified, wherever fire reaches a treatment unit;
2) Fire suppression is facilitated;
3) Dispersed treatments slow fire growth, and facilitate the establishment of containment lines in a wildfire event;
4) Fuel treatment units limit fire spread in the heading direction, which results in the greatest reduction in fire size and severity;
5) The topology of the treatment units is part of a spatial pattern that reduces fire spread rates and intensities.

The importance of rate of spread for each fuel type requires that treatment planning should target specific weather conditions. Weather conditions that should be considered by the planning scenario are those that historically have led to large and severe wildfires.

The spatial pattern and dimensions of treatments on the landscape should be guided by the history of wildfire events (e.g. size distribution, dominant direction of spread, weather conditions). The most efficient partially overlapping pattern is based on this information and
generates a spatial pattern of treatments that overlap perpendicularly to the main direction of fire spread under the targeted weather conditions. To maximize this effect, with restrictions for treatment location, size and percentage of treated area, the treatment pattern that originates the greatest reduction in overall fire spread rate with the minimum treated area is taken into account. Because treated areas are not connected, the procedure is more flexible in accommodating spatial variability and constraints.

FlamMap is used to produce maps of rate of spread, flame length and fireline intensity. GRID files for altimetry, slope and aspect are created from the digital terrain model. This information is joined with fuel model maps to form the LANDSCAPE file, the mapping base to FlamMap simulation, supplemented by information on weather, wind and fuel moisture. Fire behaviour metrics (rate of spread, flame length and fireline intensity) can be calculated for different scenarios. This information is calculated using the Minimum Travel Time (MTT) algorithm which calculates and chooses the fastest fire paths using a two-dimensional model of fire spread/growth. The model determines the growth and behaviour of fire for the set of fire paths with the shortest delay time from the ignition source set. During the simulation weather and fuel moisture variables are kept constant.

2.4 Final remarks

Fuel treatment planning is a theme that has been object of managers and researchers attention. This interest is recently growing, motivated by the increasing occurrence of extreme large wildfires. This scenario, associated with the scarcity of resources and changes in the social and economic framework, which has led to a growing attempt to optimize fuel management planning. Prescribed burning is one of the most appropriated treatment techniques, considering the actual framework.

The increasing availability of decision support tools and digital information has led to the development and application of simulators, complementary with traditional planning methods. The use of this simulators should be validate by it’s applications to real scenarios.
3. Spatial simulation of fire spread: two different approaches applied to Tapada de Mafra, CW Portugal

3.1. Introduction

Diferent tools to simulate the spread of forest fires have been developed in recent decades, driven by vulgarization of the information in digital format, and particularly with the increasing development of Geographic Information Systems (GIS).

In this initial approach, we tested the use of two fire spread simulatores applied to the landscape of Tapada de Mafra. In a simple way, we test FARSITE, fire area simulator (Finney 1997) and Landlord, spatial modelling system v1.2 (Heathfield 1999), using available information and developing the required inputs.

3.1.1. Study area

Tapada de Mafra is a public land estate with 834 ha, located in CW Portugal, north of Lisbon. The soil occupation is varied, being constituted by pure mixed stands of *Pinus pinaster*, *Pinus pinae*, *Quercus suber* and *Eucalyptus globules*, and riparian vegetation areas along the main water lines. A significant area is occupied by shrublands (*Erica* sp., *Ulex* sp.) and rangelands for wildlife feeding. The estate is surrounded by a high wall which serves as an effective fuel break for surface fires.

3.1.2. Objectives

The existence of a GIS for Tapada de Mafra area provide necessary data to use in simulations of fire behavior at landscape level.

The purpose of this study was to test the application of two distinct systems for simulation of fire propagation and production of maps of the affected area.

3.2. Fire simulators

3.2.1. Landlord – Spatial modelling system (version 1.2)

Landlord is a component-based, open-architecture spatial modelling system. It’s implemented as Windows software. It looks a bit like a GIS, but is quite different. In Landlord
maps are objects, not files. Landlord accepts .bmp or .img format images. Map objects reside in map collections. Map collections interact with spatial processes, which take one or more maps as inputs and make changes to one or more maps as output. All of these components are organised and configures within workspaces which can be saved and reopened (Heathfield 1999).

**The ModMED landscape fire modelling (Heathfield and Rego 1997)**

Landlord software uses a specific process to simulate the spread of fire, the ModMED landscape fire modeling, describing the value of variables with values

The landscape is represented using a raster mapping system, which is a grid of maps with variables values assigned to pixels. In modelling fire at the landscape level, we are simply trying to predict the extent of spread of a fire once it started. The role of the landscape fire model is to come up with a list of cells (pixels) which have been fire-affected by the time the fire goes out. The fact that it only interested in predicting the extent of spread makes the requirements, and therefore the approach, slightly different from most other fire models, which are usually concerned with predicting the rate of spread.

Model treats the fire event as instantaneous. Although it is obvious that an actual fire event takes at least some time to occur, the model treats fire as an instantaneous event. Wind speed and direction are constant for the duration of simulation. The sequence in which the pattern is developed is not intended to correspond to any likely sequence of fire pattern development in an actual fire. The sole objective of the simulation is to predict the damage pattern which results when the fire has gone out.

In order to predict the extent of a fire, the simulation is iterative, which means that a set of calculations are performed over and over again to produce a result. At the first iteration, when the fire begins, the fire starts in one or more cells. Each raster cell which is alight (a source pixel) has one opportunity to ignite any adjacent cell, which are not alight (target pixel). Depending on the conditions, the model calculates a probability value (0-1) for the spread of fire from source cell to each target cell - the contagion probability. A random number (0-1) is generated, and if this is less than the probability calculated, then the target raster catches fire. At the end of each iteration, the source pixels stop being on fire and the newly alight target pixel become the new source cell. As long as there are still cells alight, the simulation continues by beginning another iteration. When there are no pixels left alight, the simulation finishes, and a list of burned pixels has been collected. This approach handles fire as a contagious process.
Factors that affect contagion probability

These are the factors which are used to calculate the probability of contagion:

1. Slope
2. Wind (speed and direction)
3. Fuel horizontal continuity
4. Fuel moisture content.

A factor value is calculated for each, and then each factor value is weighted according to the model configuration.

Topographic effect is expressed by the effect of slope. If the source cell value is lower than in neighboring target cell, it is likely that the fire spread successfully between the two. Slope influence is more effective for steeper scenarios. Contagion probability is reduced where the slope, in the direction of fire spread, is downhill, and increased when it is uphill. The model establishes a nonlinear relationship between the slope and the slope factor value.

The wind speed and direction are defined constants for the simulation. If the wind is blowing strong and with direction of fire propagation, increase the effect on ignition between ignited cell and target cell, the probability of progression is greater and the contagion probability increases.

The effect of the fuel is expressed through two factors: fuel humidity and horizontal continuity.

The horizontal continuity of fuel is a structural property of vegetation. The model expresses these values in a raster map. A low value indicates a patchy or discontinuous distribution, and thus the probability of infection is lower. The fuel moisture reflects the state of vegetation, determining the probability of extinction in a cell. The model combines the two factors providing a single fuel factor.

Each of these three factors can be weighted by the user in the configuration options. Model use these three factors multiplied and raised to the power 1/3 (geometric mean) to give the final contagion probability.

3.2.2. FARSITE - Fire Area Simulator (Finney 1998)

We used FARSITE model (Finney 1998), a deterministic fire growth simulation model, to simulate fire behaviour in a spatially explicit way based on maps of fuel models, terrain, and weather variables. Topography and fuel data are inputs from GIS in raster format and weather and wind are input as stream of data. Fire behaviour models used by FARSITE are specific to
distinct types of fire, like surface fire, crown fire, spotting, etc. Fire growth is represented as an expanding elliptical wave-front. The fire line is assumed to be the edge an increasing wave. This frontline is defined as a series of vertices, where the fire behaviour calculations are made.

At each of these points (vertices), fuel, topography and weather are acquired from the input data (Figure 3-1) and used to calculate fire behaviour and spread direction.

Raster files are created by interpolating the fire behaviour values from neighbour vertices, indicating Arrival Time, Fireline Intensity, Rate of Spread, Flame Length, Heat/Area, in any resolution (independent of landscape resolution).

The simulation process (figure 3-2) consists of:

1. Importing spatial data to create a landscape (.lcp) file;
2. Generating wind, weather, fuels moisture, and others file inputs, and with the landscape file create a project (.fpj) file
3. Initiating simulation
4. Setting simulation parameters, fire behaviour options, ignitions and selecting outputs
5. Run the simulation (start, stop, adjust, restart...)
6. Output interpretation.

FARSITE provides several outputs results from the simulation, as ASCII raster map of fire behaviour parameters, vector shape file contour, and ASCII string of values.
3.3. Methodology

3.3.1. Applying the ModMed fire model to some historical fire data from Tapada de Mafra

On the 23rd August 1975, a large fire burned for three days, starting at 15:00. Each night the fire went out and re-ignited in the next day as the humidity fell.

We assumed:

• We were modelling a surface level (litter and shrub layers) fire contagion, using horizontal continuity of the lower levels of vegetation for modelling the spread of fire.

• The moisture content would be similar across the whole landscape and the land use patterns for 1975 where the same as in 1974.

• Same average wind speed was used for the three days; wind direction was determined by the valley of the major water stream.

The simulation data and their preparation

Four map files (resolution 12.5 m) were used:
- A map of the outline of the Tapada;
- An elevation map for the Tapada and surrounding area;
- A map showing 20 land use types for Mafra and surrounding area in 1974;
- A map showing the outlines of the fire-affected area.

In each case, data were available for a rectangle which included the (non-rectangular) area of the Tapada. However, we only used data from within the Tapada because the estate is surrounded by a high wall which serves as an effective fire break. This unnatural situation helped to simplify the modelling.

The original maps were stored as shape files. They were imported to Idrisi to produce raster grid maps.

In each case, data were available for a rectangle which included the (non-rectangular) area of the Tapada. However, we only used data from within the Tapada because the estate is surrounded by a high wall which serves as an effective fire break. This unnatural situation helped to simplify the modelling. All the maps where clipped with the outline of Tapada de Mafra estate. The outline of the Tapada was held as a shape file (ArcView version 3.2). This was imported to Idrisi to produce a raster grid map in which the rasters inside the Tapada had the value '1' and those outside value '0'.

We use the following grid map specification for the Tapada area. The result is shown below. (figure 3-3)

<table>
<thead>
<tr>
<th>Bottom left: (97000,220000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top right: (102000,2232000)</td>
</tr>
<tr>
<td>Columns: 400</td>
</tr>
<tr>
<td>Rows: 240</td>
</tr>
<tr>
<td>Resolution: 12.5 m</td>
</tr>
</tbody>
</table>

---

Figure 3-3. Grid specification and grid map of Tapada de Mafra area.
Preparing the elevation grid map

The source file was stored as a shape file (ArcView version 3.2). We used the ArcView extension called 'Shape to DXF converter' to produce a DFX file. Next, we imported it to Idrisi32 to get an Idrisi vector file. This was rasterised onto a background image using the Idrisi 'LineRas' function. The background image was created using the Idrisi 'Initial' function.

Next, we used the Idrisi 'Intercon' function to build a raster surface from the rasterised lines. Finally, we used the Idrisi 'Window' function to cut out the area of interest, to produce an elevation grid map with the defined specifications. This was multiplied by the Tapada area grid (using Landlord 'Maptools'), to limit the data to the Tapada extent.

The resulting grid map was imported to Landlord 1.2 as shown in figure 3-4.

![Figure 3-4. Digital elevation model (DEM) map of Tapada de Mafra area.](image)

Preparing the land use grid map

The source file was again an ArcView 3.2 shape file. This was imported to Idrisi for Windows to produce an Idrisi vector file. This was rasterised using the Idrisi 'Polyras' function.

The conversion process had lost information about the meanings of the polygons (the land use classes associated with each area). These relationships were restored using a basic program which reclassified each raster value to the appropriate land use class. We added category names for each land use type by manual editing of the Idrisi image documentation file. Finally, we removed the information from outside the Tapada using the Landlord 'MapTools' to multiply a grid of the Tapada area (0 or 1) by the land use grid.

The resulting grid map is shown in figure 3-5.
We assumed that we were modelling fire contagion for surface fuels. The fire might affect the tree canopies, but the spread of the fire would be in litter and shrub layers. So we were only interested in the horizontal continuity of the lower levels of vegetation for modelling the spread of fire.

To translate the land use classes to horizontal fuel continuity values we prepared a table which contained estimates of fuel horizontal continuity for each land use type classes. Then we use a hand-made program to translate the land use classes to fuel horizontal continuity values. The resulting map is shown below (Figure 3-6).
**Estimating the fuel moisture using riparian zones**

We had an ArcView map of water courses in the Tapada, and rasterised this into Idrisi with values from 0 to 4, thus:

We then used the ModMed Seed Flow model to produce a more diffuse pattern. We used the linear diffusion pattern with a maximum range of 100 metres to give the map shown below.

![Image 1](image1.png)

*Figure 3-7. Water lines map and fuel moisture estimation.*

**Estimating the fuel moisture using aspect**

Another possible source of fuel moisture pattern is aspect. We produced an aspect grid using the Idrisi 'Surface' function (figure 3-8), and then used Landlord 'MapTools' to reorder the values to range from 1 for exactly south-facing and 3 for exactly north-facing.

![Image 2](image2.png)

*Figure 3-8. Fuel moisture adjustment map using aspect*
These two approaches made it possible to generate possible maps of estimated fuel moisture content. After testing with several combinations, we decided to use a uniform map with all areas having a fuel moisture content of 10%.

**Winds**

From weather reports from nearby weather station (Sintra), we estimated the direction and speed of the mid-afternoon winds for the three fire days.

We discovered a bug in the model which reversed the direction of the wind effect. To work around this problem, we added 180 degrees to the direction which we really wanted, so 30° became 210° when entering the settings.

We set up a workspace using the ModMed Fire process model. The default settings were used, with wind information set to 7m/s wind speed and 210 degrees for wind direction.

**The damage maps**

The damaged area map from the 1975 wildfire was imported to Idrisi from ArcView shape files to give binary raster grids (each raster is either damaged or undamaged). These damage maps show approximate areas of damage. The outlines were sketched by forest rangers onto paper maps. The pattern of actual damage (approximate) is shown in the map below.

![Figure 3-9. Burnt area of the 1975 wildfire.](image)
3.3.2. Applying FARSITE using custom fuel models developed for Tapada de Mafra

The objective of the study were to determine the areas within Tapada de Mafra with a higher potential of summer fire hazard, enabling a subsequent test of diverse management strategies designed to minimize the consequences of a wildfire.

The existing Tapada de Mafra GIS was used to generate the raster themes: elevation, slope, aspect and fuel models. A field survey of the mapped vegetation patches (land use map of 1995) was carried (summer 2000), correcting their boundaries where necessary, and assigning custom fuel models developed with BEHAVE system (Burgan and Rothermel 1984). Data to develop the fuel models was obtained from indirect sampling procedures, namely line transects, and was subsequently used to estimate loading by fuel type, condition and size-class; published information was the source for the remaining fuel inputs. From this process result 21 custom fuel models (Table 3-1).

Table 3-1. Custom fuel models parameters (metric units) used in the FARSITE simulations

<table>
<thead>
<tr>
<th>Fuel model</th>
<th>Fuel loading t/ha</th>
<th>Surface area to volume ratio 1/cm</th>
<th>Fuel Depth cm</th>
<th>Moist. of extinct. %</th>
<th>Heat content kJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1h 10h 100h Live H Live W</td>
<td>1h Live H Live W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>8,340 4,980 1,010 0,070 5,900</td>
<td>60 84 71</td>
<td>70,100</td>
<td>40</td>
<td>21316</td>
</tr>
<tr>
<td>15</td>
<td>7,690 4,260 1,010 0,090 4,330</td>
<td>63 84 57</td>
<td>49,990</td>
<td>40</td>
<td>21000</td>
</tr>
<tr>
<td>16</td>
<td>5,780 2,290 1,010 0,520 0,001</td>
<td>61 84 65</td>
<td>21,340</td>
<td>40</td>
<td>19575</td>
</tr>
<tr>
<td>17</td>
<td>5,580 2,380 1,010 0,110 1,100</td>
<td>53 84 63</td>
<td>10,360</td>
<td>40</td>
<td>19947</td>
</tr>
<tr>
<td>18</td>
<td>5,200 6,010 3,000 0,090 0,000</td>
<td>71 84 35</td>
<td>7,920</td>
<td>40</td>
<td>18973</td>
</tr>
<tr>
<td>19</td>
<td>5,040 2,000 1,010 0,020 0,000</td>
<td>70 84 35</td>
<td>4,880</td>
<td>40</td>
<td>19038</td>
</tr>
<tr>
<td>20</td>
<td>5,870 3,900 0,000 0,070 5,580</td>
<td>68 84 73</td>
<td>85,040</td>
<td>29</td>
<td>21551</td>
</tr>
<tr>
<td>21</td>
<td>3,630 1,170 0,000 0,380 0,001</td>
<td>65 84 61</td>
<td>17,370</td>
<td>25</td>
<td>18908</td>
</tr>
<tr>
<td>22</td>
<td>3,210 1,570 0,000 0,070 0,000</td>
<td>63 84 75</td>
<td>4,880</td>
<td>25</td>
<td>18694</td>
</tr>
<tr>
<td>23</td>
<td>6,230 3,740 0,000 0,070 7,380</td>
<td>63 84 62</td>
<td>0,120</td>
<td>35</td>
<td>21284</td>
</tr>
<tr>
<td>24</td>
<td>2,980 2,440 0,000 0,070 5,130</td>
<td>70 84 70</td>
<td>74,980</td>
<td>35</td>
<td>22123</td>
</tr>
<tr>
<td>25</td>
<td>2,110 1,350 0,000 0,200 2,850</td>
<td>70 84 68</td>
<td>54,860</td>
<td>29</td>
<td>21681</td>
</tr>
<tr>
<td>26</td>
<td>0,001 0,000 0,000 0,540 0,000</td>
<td>81 84 57</td>
<td>49,990</td>
<td>25</td>
<td>18964</td>
</tr>
<tr>
<td>27</td>
<td>1,120 0,001 0,000 0,160 1,680</td>
<td>68 84 61</td>
<td>35,050</td>
<td>29</td>
<td>20663</td>
</tr>
<tr>
<td>28</td>
<td>5,650 4,420 0,000 0,020 7,060</td>
<td>74 84 71</td>
<td>99,970</td>
<td>29</td>
<td>22316</td>
</tr>
<tr>
<td>29</td>
<td>2,580 1,100 0,000 0,490 0,001</td>
<td>80 84 52</td>
<td>24,990</td>
<td>25</td>
<td>17769</td>
</tr>
<tr>
<td>30</td>
<td>2,440 1,370 0,000 0,070 1,260</td>
<td>78 84 61</td>
<td>10,060</td>
<td>25</td>
<td>18750</td>
</tr>
<tr>
<td>31</td>
<td>4,120 1,050 0,000 0,040 0,000</td>
<td>79 84 75</td>
<td>3,960</td>
<td>25</td>
<td>17367</td>
</tr>
<tr>
<td>32</td>
<td>1,390 0,000 0,000 0,610 0,000</td>
<td>84 84 35</td>
<td>29,870</td>
<td>25</td>
<td>16686</td>
</tr>
<tr>
<td>33</td>
<td>0,000 0,000 0,000 0,180 0,000</td>
<td>84 84 35</td>
<td>14,940</td>
<td>25</td>
<td>16686</td>
</tr>
<tr>
<td>34</td>
<td>2,650 1,010 0,000 0,340 0,000</td>
<td>80 84 35</td>
<td>10,060</td>
<td>25</td>
<td>16988</td>
</tr>
</tbody>
</table>
The simulation data and their preparation

Landscape file

Theme maps were created in ArcView 3.2 using Spatial Analyst. Shape format maps where first converted in grid raster format, with a resolution of 10 meters. These grid maps had been exported as ASCII grid, to be used as inputs in FARSITE landscape. Landscape file was created with the required GIS themes for elevation, slope, aspect, fuel models and canopy cover.

Weather, wind and fuel files

This initial approach uses weather data collected in a meteorological station located within the Tapada area, for the period of 10 to 17 July 2000, which should reflect an example of the typical summer situation.

Beside the custom fuel models information, FARSITE also requires stream data (space delimited ASCII format) for fuels moistures. This information is used to begin the process of calculating site specific fuel moistures at each time step during the simulation. Fuel moistures are specified for 1h, 10, 100h, live herbaceous and live wood fuels. For this simulation we used values of 8% for 1h fuel, 10% for 10h and 100h and 100% for live fuels, for a moderate weather scenario.

After some tests simulation duration was set to start 14/July at 14:00 and end 16/July at 22:00.
3.4. Results

3.4.1. Landlord fire simulation

We ran the simulation several times by setting fire to a small area around ignition point, and found that the model typically predicted a spread in a more westerly direction than actually happened. Either the predicted fire affected a very small area, or if it spread to the main area of high fuel continuity, it would burn a large area westward (uphill, with a following wind and good fuel availability). A typical result of a larger fire is shown in figure 3-11.

![Simulated damage - Mafra 1975 fire](image)

Figure 3-11. Example of an output map of the simulation.

The model typically predicted spread in a bigger area than it actually happened. A problem is the fact that we are not sure what, if any, fire-fighting actions were taken at the times of the fires: the eventual pattern of each fire may have been greatly affected by such interventions.

It seemed that the wind and topography could be considered to be ‘driving’ the spread of the fire, and the fuel properties were limiting the spread.

The wind directions which we used seem to be more easterly than indicated by the actual damage pattern. Perhaps the local topography either at Sintra (where the winds were measured) or at Mafra meant that the winds were actually rather different in the two places.
The fuel horizontal continuity map which we estimated was no more than an educated guess. The default settings for the fire model make the contagion probability very sensitive to changes in fuel continuity between about 50 and 70 (figure 3-12) and the fire starting area in the simulations contained a mixture of fuel HC values ranging from 10 to 60 so it’s quite likely that the fire patterns we simulated were too strongly influenced by the Fuel HC map.

3.4.2. FARSITE fire simulation

FARSITE simulation runs for a period of 2 days and 8 hours. Ignition point was located proximally to the buildings area, in the north-centre of Tapada.
Burned area, at the end of simulation, totalizes 818 ha. Is notorious the effect of changes in fire propagation during night time, resulting in a lower increase in the burning area (Figure 3-14). In most of the area fire from reach the outside wall during the simulation period.

**Output maps**

We test to export results of the simulation as ASCII raster maps. Fire line intensity, Rate of spread and Time of arrival had been imported to ArcView GIS and converted in grid format.
The result show that most of the area burn with a low intensity fire (below 500 kW/m). Some areas with more intense fire behaviour were identified in this simulation.

![Rate of spread map, resulting from FARSITE simulation.](image)

The resulting map for the rate of spread also show the location of some areas with faster fire spread, even if the simulation conditions were moderate.

3.5. Conclusions

Both programs are proven to work as simulators fire spread in the landscape. Landlord results were more limited, since it only simulates the potential damage area, i.e., the area potentially affected by fire. It is also less demanding in terms of inputs, which somehow is revealed in the results. The software was still in development when we tested. After the end of project ModMed no more improvement was made and at this time the software is not available.

FARSITE proved to be a program with greater capacity for simulation, producing a set of detailed results about the behavior of fire, not only in number of parameters but also in time and space detail. It is however far more demanding in information, especially in relation to meteorological variables. The quality of the results are dependent on the quality of inputs, and these variables, together with the availability of fuel models mapping may be a major limitation to effective implementation of the program. Training managers in the development of this information and in the analyses of simulation results can be an important issue in FARSITE wide application.
4. Optimizing prescribed burning to reduce wildfire propagation at the landscape scale

4.1 Introduction

Prescribed fire is frequently used to reduce understorey fuels in forest stands, with the goal of decreasing the fire hazard. The decision to apply prescribed burning (PB) in a given area rarely addresses its spatial optimization, i.e., effective fuel reduction at the plot level is not always accompanied by effective risk minimization at the landscape scale.

This study has been carried in a maritime pine (*Pinus pinaster*) area within the Forest Perimeter of Entre-Vez-e-Coura, NW Portugal. Land cover in the study area is dominated by maritime pine stands, followed by gorse and heath shrublands. Privately-owned lands surrounding the Perimeter are occupied by pine, eucalypt and shrubland, with some small and dispersed broadleaf stands and agricultural areas.
The main objective was to evaluate to what extent PB reduces fuel continuity - and consequently the risk of wildfire propagation - at the landscape level, and how to optimize such effect, by using a percolation theory approach. Percolation theory can address issues related to connectivity and conductivity in a bidimensional landscape representation, and be applied in the development of neutral models for landscape patterns.

4.2 Methods

The Forest Service has performed prescribed burns in the Perimeter from 1992 to 1999. Identification and spatial and temporal distribution of the PB areas was integrated in a GIS, and such information was used as the cartographic basis for the study, by using the software ArcView GIS and IDRISI. The FRAGSTATS (McGarigal & Marks 1995) software was used to analyze the map outputs from IDRISI in the format IMG.

Optimization of PB application involves spatial considerations but also temporal ones. This implies the necessity of establishing temporal thresholds related to PB effectiveness in the reduction of fuel hazard, which are derived from fuel dynamics knowledge. Available data from destructive and non-destructive fuel sampling was used to model fuel loading \( W \) build-up according to an exponential and time-dependent model constrained by a plateau, the "steady-state" fuel load:

\[
W = a (1 - \exp(-bt))
\]

where \( t \) = elapsed time since the last PB, in years.

The fuel accumulation curves were used to predict fuel loadings for a temporal sequence of 1 to 25 years (maximum stand age in the Perimeter), and then combined with additional published information on other fuel characteristics to generate age-specific fuel models with the BEHAVE system (Burgan and Rothermel 1984).

Fuel management activities are likely to be ineffective under extreme weather scenarios. Therefore we have simulated fire behavior with BEHAVE for each fuel model by assuming the "normal" summer scenario for the region: maximum temperature = 27\(^\circ\) C, minimum relative humidity = 55%, and average in-stand wind speed at 2 m = 5 km.hr\(^{-1}\). Live fuel moisture was set at 130%, which is the typical Summer value in the nearby Galician pine stands (P. Cuiñas, personal communication). A fireline intensity threshold value of 500 kW.m\(^{-1}\) was used to distinguish the two situations required by the study:

- non-lethal surface fire that is readily extinguished by hand-tools
- damaging fire, from moderately intense surface fire to stand-replacement fire displaying crowning activity and requiring heavy suppression efforts

Transition between the two situations occurs at a fuel age of 4 years, i.e., PB is considered effective in stopping a wildfire for an average period of 3 years since the treatment. As a result of this assumption, an "active", i.e. efficient, prescribed burnt area was calculated for each year (1992 to 1999), comprising the PB area accomplished in that year plus the patches treated in the former two years.

The effect of each year's PB active area in fuel continuity was accounted by the Largest Patch Size (LPI), calculated by FRAGSTATS (MacGarigal and Marks 1995):

$$LPI = \frac{\max_{j=1}^{n}(a_{ij})}{A} \times 100$$

which allows the quantification of fuel continuity, since it expresses as a percentage the largest continuous patch in the landscape.

The Mean Patch Size (MPS) was also determined, in order to assess the evolution of the average patch size for different fragmentation levels:

$$MPS = \frac{\sum_{i=1}^{n} a_{ij}}{n_i \times \left(\frac{1}{10000}\right)}$$

We attempted on a first stage to evaluate the effect of the Forest Service PB activity during the study period. Two approaches were taken:

1. Considering the Perimeter area only, ca. 1000 ha, where maritime pine stands (approximately 640 ha) corresponds to the potential area that can be subjected to PB.

2. Considering a 2400 ha area that includes the Perimeter plus its surrounding area, and maintaining the same PB area.

Two land cover classes were considered for 1, respectively maritime pine and non-maritime pine. This case addresses only potential fire propagation within the Perimeter, and excludes the remaining area, which is considered not-flammable.

For the global area situation an initial scenario was established, clustering in a unique area the surfaces where selection by fire was higher than expected (Moreira et al. 1999), meaning that they are the preferred area for wildfire propagation. The remaining area (agriculture, rocky terrain and broadleaves) was deemed not-flammable.

The areas subjected to PB were given a "flammable" or "non-flammable" status that varied with time since the last PB, according to the fuel and fire behavior dynamics study.

On a subsequent second phase, we established hypothetical scenarios for the spatial design of PB treatments, considering its optimization in terms of reducing fuel continuity,
respect of the recommendations that arose from ecological studies conducted in the area, and some operational issues.

For this proposal, we have only considered the maritime pine area within the Perimeter. Because it is a continuous stand, its LPI value in the absence of disturbance equals 100% of the area. The 1st year intervention aims to "isolate" the Perimeter's area from the surrounding private property areas where the risk of fire occurrence is high. The main objective in the following years is to break fuel continuity in the pine stand such that MPS is reduced.

In accordance to the recommendations issued from the biodiversity studies in the area, PB periodicity should be higher than 5 years. In addition, PB areas are assumed efficient (active) for 3 years.

Two hypothetical scenarios are considered:

Scenario 1. PB annual area was based in the method of Turner et al. (1993), such that an equilibrium in landscape dynamics would be maintained. According to this methodology, the maximum annual PB area should be 96 ha, which in 3 years results in 288 ha (45% of the total pine area) of active area. In this case, we tried to create discontinuity through fewer but relatively larger plots that seek to "intercept" all the pine stand and yield less annual PB acreage.

Scenario 2. The annual PB area is a function of the total available area to burn and the recommended fire interval. Considering that maritime pine area in the Perimeter is 640 ha, an interval of 5 years results in 128 ha/year. After 3 years (the efficiency lapse of time) an active area of 384 ha (60% of the pine acreage) would be attained in the optimum situation. This scenario comprises more and smaller PB plots that yield higher burned area per year. This highest plot dispersal decreases the probability of extensive continuous patches beyond the PB effectiveness period.

The burned plots were - whenever possible - established along the road network with a width of 200 m and not exceeding 50 ha in size; this former value was based on the average size of the management unit typically used by the Forest Service, and results in a defensive structure that maintains the traditional network division but it is spatially and temporally dynamic.

4.3. Results

4.3.1. Analysis of the prescribed fire effect in the 1993-1999 period

Seven scenarios were considered for the period between the winter of 1992 (1992/93 burning season) and the spring of 1999 (1998/99 season), reflecting the PB area evolution. PB use in the Perimeter has fluctuated over the years, with an annual treated area ranging from 1
to 50 ha, and without interventions in 1996. This variation is clearly reflected by the landscape indexes (Table 4-1).

Table 4-1. Variation in the active prescribed fire area and in the LPI and MPS indexes, for the perimeter and global areas.

<table>
<thead>
<tr>
<th>Year</th>
<th>Active area, ha</th>
<th>LPI, % Perimeter</th>
<th>LPI, % Global area</th>
<th>MPS, ha Perimeter</th>
<th>MPS, ha Global area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>51.9</td>
<td>91.93</td>
<td>92.38</td>
<td>84.55</td>
<td>53.41</td>
</tr>
<tr>
<td>1994</td>
<td>53.5</td>
<td>91.69</td>
<td>92.31</td>
<td>84.33</td>
<td>53.38</td>
</tr>
<tr>
<td>1995</td>
<td>103.35</td>
<td>81.63</td>
<td>90.22</td>
<td>31.79</td>
<td>47.89</td>
</tr>
<tr>
<td>1996</td>
<td>51.45</td>
<td>89.55</td>
<td>92.38</td>
<td>84.60</td>
<td>52.23</td>
</tr>
<tr>
<td>1997</td>
<td>55.7</td>
<td>88.85</td>
<td>92.20</td>
<td>84.00</td>
<td>49.92</td>
</tr>
<tr>
<td>1998</td>
<td>10.93</td>
<td>98.21</td>
<td>94.08</td>
<td>158.18</td>
<td>50.88</td>
</tr>
<tr>
<td>1999</td>
<td>40.26</td>
<td>92.06</td>
<td>92.83</td>
<td>33.52</td>
<td>47.24</td>
</tr>
</tbody>
</table>

The LPI value decreases for both the Perimeter and the whole area with the increase of PB active area, with a less apparent and obvious effect for the global area. Decrease of the LPI value in this case is essentially explained by area removal from the largest patch, rather than by increased fragmentation; note that LPI in this case represents a substantially larger area (LPI=90% corresponds to ca. 2160 ha).

The effect upon MPS (Figure 4-3) is equally less apparent for the global area, where the existence of a great number of small patches, near the largest patch boundaries, contributes to average lower values. For the Perimeter area the PB area effect is quite evident; especially note the situation in the last year, 1999: the effect of the spatial distribution pattern of the plots is more pronounced and induces more fragmentation.
4.3.1.1. Conclusion

It can be concluded from the above results that a positive impact on fuel continuity in *Pinus pinaster* stands was achieved with the use of PB in the study area. Changes in the Perimeter's management policy have unfortunately practically conducted to the technique abandonment and do not favour the maintenance of such hazard reduction effect. Nevertheless, maximization of fuel discontinuity at the landscape level in the selection of the plots to be treated was hardly achieved, and the same amount of annually treated area could have attained a higher protection effect in some cases; an example of increased fragmentation obtained by changing the location of two plots is given in figure 4-4.

Figure 4-3. Prescribed burning active area and MPS (1993-1999).

Figure 4-4. Hypothetical modification of the spatial location of two plots in 1999.
4.3.2. Proposal of improved prescribed fire application in study area

Both scenarios display the same trend towards equilibrium in the simulated 5 year period (after the fifth year the 1st year plots can be burned again). The active area stabilizes in the third year.

The LPI value diminishing trend is the same for both scenarios, but it is more pronounced in the first case (figure 4-5). However, scenario 2 allows slightly lower values after 5 years, which can be explained by differences in the extent and location of the treated area. Fragmentation is fast with scenario 1 because the PB plots are larger, while the higher plot dispersion and treated area of scenario 2 originates an inverse situation in the fourth year.

The above is equally true for the MPS index (fig. 4-6). The higher PB plots size has clear consequences in the increase of this index after year 3, when the 1st year PB area is no longer effective. Still, such increase does not create a significantly different situation from scenario 2.
It can be concluded that options 1 and 2 lead to similar fragmentation and division degrees. Nevertheless, scenario 1 with less PB area efforts, and consequently more economical and operational feasibilities, diminishes more rapidly the extent of continuous untreated fuels.

4.4. Fire behaviour simulation using FARSITE

To examine the spatial effect of prescribed fire areas in the Pinus pinaster area we run two simulations in FARSITE, using two scenarios. The first one represents the landscape without any prescribed burning. A single fuel model was assigned to the forest area.

The other one presents the situation in 1995, when the active prescribed burning area in the perimeter was highest. In this case we used four fuel models (table 4-2). Model #14 represents the prescribed burning of the year, with less than one year of fuel accumulation; model #15 for the second year burnings and model #16 to prescribed burning areas with three years of fuel accumulation. Model #22 was used in the remaining forest area.

Table 4-2. Custom fuel models parameters (metric units) used in the FARSITE simulations

<table>
<thead>
<tr>
<th>Fuel model</th>
<th>Fuel loading t/ha</th>
<th>Surface area to volume ratio 1/cm</th>
<th>Fuel Depth cm</th>
<th>Moist. of extinct. %</th>
<th>Heat content kJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1h 10h 100h Live H Live W</td>
<td>1h Live H Live W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>2.65 1.01 0 0.31</td>
<td>2.65</td>
<td>49 85 58</td>
<td>6.71</td>
<td>40</td>
</tr>
<tr>
<td>15</td>
<td>5.02 1.01 0 0.31</td>
<td>4.28</td>
<td>49 85 58</td>
<td>10.67</td>
<td>40</td>
</tr>
<tr>
<td>16</td>
<td>6.7 1.01 0 0.31</td>
<td>5.76</td>
<td>49 85 58</td>
<td>15.85</td>
<td>40</td>
</tr>
<tr>
<td>22</td>
<td>12.6 2.13 0 0.4</td>
<td>9.71</td>
<td>52 85 58</td>
<td>50.6</td>
<td>40</td>
</tr>
</tbody>
</table>

We maintained the weather parameters constant throughout the simulation period, in order to avoid the nocturnal effect. This way, only topography and fuels change during the simulation.

The results were exported from FARSITE in grid files, and then imported to ARCVIEW. The analyses of the burnt area by fireline intensity (figure 4-7) show that in the two situations most of the simulation estimates a fireline intensity below 500 kW.m$^{-1}$. Nevertheless, in the 1995 scenario the low intensity area is greater than in the “no PB” situation, reflecting the fuel reduction in prescribed burning plots.
4.5. Final Recommendations

Some recommendations to optimize the PB effect in space and time can now be proposed. PB plots should not be too large, i.e. a maximum value in size should be assigned to each individual parcel in a given year. Taking into account that the 3-year period of effectiveness should be followed by a 2-year period without treatment, despite the hazard build-up, this will assure that continuous fuel areas will not develop in a near future.

Treatment of contiguous areas in consecutive years should also be avoided, for the same reasons. In the 5th year after burning the first plot, the plots burned in consecutive years will simultaneously reach the hazard threshold.

FARSITE simulations can be useful to select the locations for PB units, giving priority to the most hazardous situations as a consequence of fuels and topography.

Finally, it should be reminded that the present study results are meaningful only if the main objective of PB is protection against wildfire (other land management priorities, e.g. grazing, would require different fire regimes), and is not valid for extreme fire weather.
5. A simulation-based test of landscape fuel management alternatives in the Marão range of northern Portugal

5.1. Introduction

Stand-level fuel treatments modify fire behaviour and effects on a local scale (Pollet and Omi 2002, Fernandes et al. 2004, Outcalt and Wade 2004, Raymond and Peterson 2005), though the desired decrease in wildfire size and severity cannot be achieved without significantly disrupting fire spread on a landscape scale (Finney, 2001). Since the impact at this larger scale is a function of the combined effect of individual units, the treatment design — location, spatial arrangement and size of the treatments — is vital to its effectiveness.

Fuel management areas that are randomly dispersed in the landscape are on theory much less effective than strategically-placed projects (Finney 2003, Loehle 2004), which tends to be confirmed by studies of real fires (Finney et al. 2005). The challenge is therefore to maximize the hazard reduction level for a given amount of treated area — which is usually low because of funding and other constraints — by carefully choosing where to intervene and considering the overall spatial characteristics of the project. Spatial fire simulation provides an analytical framework to test the outcomes of distinct fuel and weather settings (e.g. Van Wagendonk 1996, Stephens 1998) and can be useful in fuel management planning and assessment.

An increased attention to fuel treatments is currently being given in Portugal to oppose the current trend of fuel accumulation over large areas due to land abandonment and lack of active management. A high likelihood exists that expensive but arbitrarily designed projects will perform poorly in a large fire event, thus threatening future resource allocations to fuel treatment and a well-balanced fire management policy. A landscape-level fuel management project was implemented in the Marão mountain range in 2005/06, being one of the first of its kind in the country. We characterize the collective spatial properties of the project and use fire behaviour and growth simulation to describe and analyse its effects on landscape fire propagation in comparison with the pre-treatment situation.

In a second stage we compare this management project with the proposal for treatment areas that outcome from FlamMap simulation.
5.2. The fuel treatment project

The Marão range is located in NW Portugal and spans an elevation of 600 m to 1400 m. Slopes are steep, especially on the southern and eastern aspects. Mean annual temperature and rainfall are within 10-12 ºC and 1200-1400 mm, respectively. Most of the area is communal land under Forest Service management. Fires set by shepherds to maintain and improve the quality and quantity of forage are common in the southern and eastern slopes, at lower altitudes and in the vicinity of villages, but can occasionally escape and become large; such was the case of the 1985 wildfire which burned most of the area.

The fuel management project was conceived for a 1728 ha third order watershed. Shrubland of ericaceous species (*Erica australis, E. arborea, E. umbellata*) and *Pterospartium tridentatum* is the prevailing cover type, followed by young *Pinus nigra* plantations with a well-developed shrub understorey with the same floristic composition. Less flammable cover types - riparian vegetation, broadleaved hardwoods (*Quercus pyrenaica, Q. robur, Betula pubescens*) - occur in the valley bottoms, sometimes enveloped by *Cytisus* shrubland; a few isolated stands of *Pinus sylvestris* and *Pseudotsuga menziessii* that have survived the 1985 wildfire occupy similar topographical positions.

The fuel treatment project (Figure 1) was designed by the Forest Service and consists essentially of fuel-breaks, created with prescribed fire in shrubland between November 2005 and March 2006. Most of the treated strips are located along ridge tops and adjoin or include...
rock outcrops, roads, fire breaks and recently burned patches. The objective was to diminish the extent and severity of a wildfire impacting on the area from the most probable direction of propagation (S-E), as determined by historical ignition risk and wind patterns associated to large fires in the region. On such event the project is expected to mitigate damage to forest stands within the watershed and on the lee side of the mountain.

The treatment area totalized 198 ha, ca. 11.5% of the watershed. Recently burnt areas by wildfire (2005) and prescribed fire (2003) amounted to 3.7% of the area. Fuel-break width is generally in the range of 70 to 120 m. Area-wide treatments reach 400 m in their largest dimension. Some degree of overlapping between the fuel-reduced areas was implemented, as this pattern is the most effective in disrupting fire growth and reducing the spread rate across the landscape (Finney 2001). The spatial characteristics of the project reflect a trade-off between a strategic approach and the constraints imposed by topography and accessibility.

5.3. Objectives

The objective is to test two approaches of landscape scale fuel treatment for the area, and how they affect fire behaviour parameters. The assessment involves a comparison between the fuel-break network implemented by the Forest Service and the FlamMap proposal, area-wide treatments, proposed by Treatment Optimization Model (Finney 2006, Finney 2007).

We also test two alternative wind effect options: wind blowing uphill and wind with a 135º direction (dominant wind direction for the area), as a condition to best place treatments in the landscape. Southeast winds are traditionally associated with high risk conditions, and the last large wildfire came from that direction, but some fires can initiate on bottom slopes near villages at the interface with agriculture lands.

5.4. Methods

FARSITE combines models for fuel moisture, surface fire characteristics, crown fire characteristics, fire acceleration and spotting to simulate fire growth and behaviour under heterogeneous - in space and time - weather, fuel and terrain (Finney, 1998). We have used FARSITE and FlamMap as the simulation tools, building the required fuel and terrain inputs as ArcView GIS grid files with a 25-m spatial resolution.

Two landscapes were initially generated, depicting the pre-treatment and post-treatment fuel situation. Custom fuel models (Table 1) were developed to describe the areas occupied by shrubland of different post-fire ages, after adjusting the model’s parameters to match the fire behaviour observed in experimental fires (UTAD’s data base). NFFL fuel models
(Anderson, 1982) were assigned to the remaining vegetation types (Figure 5-1 and Table 5-2). Forest canopy characteristics were based on field inspection.

### Table 5-1. Custom fuel models for shrubland in the study area.

<table>
<thead>
<tr>
<th>Fuel parameters</th>
<th>14</th>
<th>16</th>
<th>17</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 h</td>
<td>6.95</td>
<td>1.01</td>
<td>2.31</td>
<td>1.50</td>
</tr>
<tr>
<td>10 h</td>
<td>3.00</td>
<td>1.01</td>
<td>0.49</td>
<td>1.01</td>
</tr>
<tr>
<td>100 h</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Live herbs</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Live woody</td>
<td>13.92</td>
<td>2.00</td>
<td>6.50</td>
<td>3.99</td>
</tr>
<tr>
<td>Surface area to volume ratio, 1/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 h</td>
<td>43</td>
<td>27</td>
<td>37</td>
<td>27</td>
</tr>
<tr>
<td>Live herbs</td>
<td>58</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Live woody</td>
<td>52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel depth, cm</td>
<td>92.1</td>
<td>10.1</td>
<td>29.9</td>
<td>14.9</td>
</tr>
<tr>
<td>Moisture of extinction, %</td>
<td>28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat content, kJ/kg</td>
<td>22461</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


### Table 5-2. Fuel models distribution and patch characteristics in the simulation area for the pre-treatment.

<table>
<thead>
<tr>
<th>* Fuel model</th>
<th>Area, ha</th>
<th>% of total area</th>
<th>No. of patches</th>
<th>Mean patch size, ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>192</td>
<td>4.9</td>
<td>35</td>
<td>5.5</td>
</tr>
<tr>
<td>1</td>
<td>42</td>
<td>1.1</td>
<td>11</td>
<td>3.8</td>
</tr>
<tr>
<td>4</td>
<td>844</td>
<td>21.4</td>
<td>55</td>
<td>15.3</td>
</tr>
<tr>
<td>5</td>
<td>307</td>
<td>7.8</td>
<td>37</td>
<td>8.7</td>
</tr>
<tr>
<td>6</td>
<td>169</td>
<td>4.3</td>
<td>25</td>
<td>6.8</td>
</tr>
<tr>
<td>8</td>
<td>352</td>
<td>8.9</td>
<td>59</td>
<td>6.0</td>
</tr>
<tr>
<td>14</td>
<td>2039</td>
<td>51.7</td>
<td>9</td>
<td>226.6</td>
</tr>
</tbody>
</table>

* 0 = rock; 1-8 = NFFL fuel models; 14 = 1985 wildfire.

A first FlamMap simulation was made for the pre-treatment scenario, to obtain the treatment proposal from FlamMap Treatment Optimization Model (TOM). Calculations were performed at a 25-m resolution, for an ideal landscape where fuel model 14 is replaced by fuel model 16 inside the watershed area, and the treatment fraction equals the prescribed burning
plan, setting 400 m as the maximum treatment dimension. The proposed treatment grid was used to create the landscape file to simulate fire behaviour with the same environmental parameters than the other two scenarios. The same procedure was adopted for the two wind scenarios, SE wind and upslope wind. Landscape scenarios will be compared in two sets, according to wind direction (Table 5-3).

Table 5-3. Landscape scenarios tested in the simulations.

<table>
<thead>
<tr>
<th>Landscape scenarios</th>
<th>FARSITE simulation</th>
<th>FlamMap simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SE wind</td>
</tr>
<tr>
<td>Pre treatment – situation without fuel management</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>RX plan - fuel-break project</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>TOM plan: SE wind (135º)</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>TOM plan: upslope wind</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fire growth was simulated in FARSITE for an extreme meteorological event, by using the 97th percentiles - i.e., higher values occur in 3% of the days of the year - for air temperature (35°C) and relative humidity (25%) and the corresponding value of 5% for dead fuel moisture content, obtained from data analysis of a weather station located in the area. This constant weather stream, with a 6-m height wind speed and direction respectively of 30 km.h⁻¹ and 135º was held for the entire simulation, in order to highlight the role of fuel in fire behaviour. The inputs of live fuel moisture content were based on previous sampling experience with the different vegetation types in the peak summer period.

Figure 5-2. Proposal for fuel treatment location from the Treatment Optimization Model (TOM), respectively for SE wind (left) and upslope wind (right).
The simulations were not constrained by fire suppression activities that would have obscured the fuel treatment effect. Edge effects were avoided by not limiting fire growth to the watershed boundaries: a simulation area of 3945 ha that encompassed the treated watershed was used. Crown fire was enabled, as well as spotting as a contributor to fire growth.

To compare the proposal treatment scenarios, fire growth was simulated in FlamMap. This software simulates fire with the same models as in FARSITE, but weather and fuel moisture variables are kept constant during the simulation. A 6-m height wind speed and direction respectively of 12 km.h\(^{-1}\) and 135° was used to create wind maps using WindNinja software, in order to reflect the interaction between wind and topography. For the second scenario an upslope wind of 12 km.h\(^{-1}\) at 6-m height was used.

An ignition line was located outside and southeast of the study area, replicating the 1985 wildfire approach to the watershed and the northern limit of a 1998 wildfire. The simulation ran for a 24-hour period of, but we have restricted the comparative analysis between the pre- and the post-treatment to a 10-hour period, from the moment fire entered the watershed until it burned its entire area in the pre-treatment situation.

FARSITE and FlamMap outputs were analysed with the software ArcView Spatial Analyst 2.0, from which the presented results (all referred to the watershed area) are derived. We have selected for comparison between fuel scenarios the fire front time of arrival, rate of spread and fireline intensity, mapped in grid format. These layers were complemented with vectorial information and tables.

5. Results and Discussion

5.1. FARSITE simulation

The overall fire behaviour potential in the simulation area is very high. The most hazardous fuel models (NFFL 4 and 14 - 1985 wildfire) occupy 73% of the watershed, model 14 displaying a quite distinct and larger patch size. Hence, fire progression is fast in the pre-treatment situation and is delayed by the riparian zones only. After 5 hours of simulation 75% of the watershed has burned, and after 10 hours 99% has burned (Figure 5-3).
Figure 5-3. Fire line length and cumulative burned area in the watershed, before and after the fuel treatment, and as a function of time elapsed since the wildfire enters the watershed.

After the treatment the effect of the first fuel-break is immediately apparent one hour after the simulation begins, thus reducing fire growth. After 5 hours only 40% of the area has burned, and after 10 hours 11% of the area remains intact, corresponding to fuel-reduced plots but also to untreated vegetation that has benefited from the fire behaviour mitigation effect induced by the treated areas. It is important to note that we have assumed a worst-case scenario by allowing the recently treated areas to burn, although lack of continuity and a very low dead-to-live fuel loading ratio should prevent fire spread in the Erica-dominated shrubland for a period of up to 3 years after prescribed fire (pers. observ. in extreme weather wildfires). Nevertheless, not all fuel-reduced plots were totally burnt at the end of the simulation period.

Figure 5-4. Fire front time of arrival before (left) and after (right) the fuel treatment.
The treated areas disrupt and fragment the fire front, which paradoxically increases the fire front length (Figures 3 and 4). This was noticed also by Stratton (2004) and is essentially caused by a convoluting effect that is formed as the fire flanks around the treated plots. The modified fire fronts are of course slower, less intense and smaller in size.

Fire behaviour mitigation by the treatment over the project area is obvious, in the fuel-reduced plots and on the whole landscape (Figure 5-5). Pre-treatment rate of spread and fire intensity were reduced, on average, by 35.6% and 33.5%. The classification of fire spread rate (Figure 5-6) shows a predominance of class III (6-15 m.min\(^{-1}\), 41% of the area) before the treatment, followed by class IV (16-30 m.min\(^{-1}\), 23% of the area). After implementing the fuel treatment the surface with a spread rate higher than 5 m min-1 was reduced, whereas the area ≤ 5 m.min\(^{-1}\) increased to 58%, i.e. 24% more than before. This would allow earlier wildfire containment employing fewer resources.

Figure 5-5. Classification of fire behaviour before (left) and after (right) the fuel treatment: rate of spread (top, m.min\(^{-1}\)) and fire line intensity (bottom, kW.m\(^{-1}\)).
Fireline intensity in the class > 4000 kW.m\(^{-1}\), i.e. beyond the effectiveness threshold of fire suppression employing direct attack, is markedly affected by the treatment, from more than half of the area to one third of it, which is a 41% decrease. The portion of the watershed where fire suppression would be successful by ground attack (< 2000 kW.m\(^{-1}\)) increased from 25% to 47%, i.e. suffered a relative increment of 88% (figure 5-6). This reduction in fire intensity also has implications on the ecological severity of the fire, not just because the overall heat release is diminished but also because the spatial pattern of fire intensity is much more heterogeneous after the treatment, as visible in Figure 5-5.

Design deficiencies in the fuel management project can be perceived from the simulation results, namely the insufficient width or length of some fuel-breaks, allowing the fire to breach or bypass the treatments with relative ease. The effect of spotting was not relevant before the treatment, because the head fire front advance was sufficiently rapid to assimilate ignitions caused by spotting. After the treatment is in place, the simulation shows that spotting over the treated area develops into new fire fronts following a radial pattern that rapidly reach the next fuel-break. This should be even more pronounced in the real world, because the wind turbulence that characterizes ridge tops (an effect not addressed by FARSITE) is favourable to spotting. Again, this stresses the importance of fuel-break width and the role of fire crews in suppressing spot fires.

The results of the simulations can be viewed as the minimum performance possible of the treatment, since the simulations do not consider its effect in blocking fire growth and suppression effectiveness. However, FARSITE can also account for these outcomes, which allows cost-benefit analysis based on the estimation of the protected surface (i.e. prevented from burning) per unit of fuel-reduced area.
5.2. FlamMap simulations

In the SE wind scenario, the treatments effect in fire spread is visible from the first hour of simulation (figure 5-7), and this effect is more obvious in the optimized proposal, since the first treated area is almost adjacent to the ignition line. After the first 3 hours of simulation 50% of the watershed has burned in the untreated scenario, and for both treatment alternatives only one third of the area has burned. However, from this point on the prescribed burn effect in reducing fire spread is less evident. Similar burned values correspond to the two treatment scenarios, which overlap with the untreated scenario 8 hours after ignition. Consequently, in order to benefit from the treatments fire suppression should be as fast as possible.

![Figure 5-7. Cumulative burned area in the watershed, before and after the fuel treatment, and as a function of time elapsed since the wildfire enters the watershed. Left - SE wind; Right - upslope wind.](image)

In the second simulation, with fire spread driven by an upslope wind, the first impression is that landscape vulnerability to fire is minor. The area burned after 10 hours is only 25% of total watershed area, in the worst case. In this simulation, the treatment effect is more remarkable after the second hour, and the optimization scenario is always less effective in slowing fire spread.

The ROS and FLI maps (figure 5-10 and figure 5-11) resulting from the simulations show some differences between the two simulation options and testify to the fuel treatment benefits in the area. The results are consistent with those obtained for fire spread in the different landscape scenarios.

Both treatment alternatives attain similar impacts on rate of spread. The classification of fire spread rate (Figure 5-9) shows a predominance of class III (6-15 m.min⁻¹), in all simulation scenarios with SE wind. The main change is that the surface with a spread rate higher than 15 m.min⁻¹ was reduced by treatments, whereas the area ≤ 5 m.min⁻¹ increased to
near 50%. Both treatments increase the proportion of area burned in classes I e II, but the TOM scenario is more efficient in reducing the extreme classes’ values.

Results are very similar in all upslope wind scenarios, with a strong dominance (>70%) of class I in all situations. Upslope simulations result in lesser differences between scenarios, but the TOM proposal is slightly more efficient, decreasing the extreme classes and increasing by 10% the surface corresponding to ROS <2 m.min⁻¹.

Fireline intensity results (figure 5-9) show that the implemented prescribed fire plan substantially increases class I (<500 kW.m⁻¹) area, whereas the TOM proposal is more effective at decreasing the extreme (>10000 kW.m⁻¹) class surface. Both scenarios increase classes II and III (500-4000 kW.m⁻¹), because area is transferred from the two upper classes (-22.3% in the
actual treatment and -25.2% in TOM). In the untreated scenario more than 68% of the surface was allocated to the two upper classes.

In the upslope simulation and in the absence of treatments ground attack would be successful in more than 75% of the area, i.e., where fireline intensity < 2000 kW.m\(^{-1}\). After treatment such effectiveness increases to more than 80% with small differences between the two proposals.

Figure 5-10. Classification of rate of spread (m.min\(^{-1}\)) before and after the fuel treatments for the SE wind (top) and upslope wind (bottom) scenarios.
5.6. Conclusion

Analysis of the simulation results indicates that the fuel treatments pattern in the Marão range is successful in diminishing the potential for large-scale wildland fire, reducing its growth rate and increasing the probability of successful suppression. Conceptual problems in the project’s design are also revealed that recommend the expansion in width of the fuel-breaks and a higher level of overlapping between successive strips. As the results reflect the project’s first year of implementation it is expected that in the future it evolves towards a
mosaic of fuel treatments, a more efficient approach than the establishment of a network of fuel-breaks.

The spatial simulation of fire growth and behaviour is a powerful tool to examine alternative scenarios of fuel management, and it is particularly appropriate for asking “what-if” questions. The planning and decision making process can therefore be enhanced by this approach, which can complement and contribute to improve guidelines for fuel-break construction and maintenance (e.g., Agee et al. 2000; Rigolot 2002b).

Considering that the outcome was similar, FlamMap’s optimization process was not particularly advantageous over the prescribed fire planning carried out by experts. The fuel-break model (a fuel management strategy based on isolation) is generalized in southern Europe. Fire- and fuel-breaks may well be narrow in most instances, but their high density can approach a fuel treatment structure with near complete overlap (Finney 2001). The topology of Marão prescribed fire plan presents some similitude with the complete overlap model, especially in the case of the SE wildfire scenario. Because some overlap was visible between the proposed treatments and those treatments that were implemented, and considering that the percentage of treated area is low, it may be advisable to further optimize the spatial pattern by combining the various scenarios. One obvious deficiency of the treatment optimization process is the absence of an option to anchor treatments (e.g. on access routes), which is quite important in prescribed fire operations.

5.7. Final considerations

Most of the available studies on fuel treatment planning strategies refer to North-America and Australia. Fire is used to achieve distinct land management objectives, but literature on the landscape-level planning of such burns is almost nil. Current knowledge on the dynamics of fuel accumulation after treatment or disturbance is acceptable for several vegetation types in the Mediterranean, but empirical information on how fuel accumulation (and time since treatment) translates into treatment effectiveness is quite scarce. The effect of repeated treatments on fuel dynamics and changes in fuel structure and composition is also poorly known.

The offer of fire simulators with application to the problem of selecting locations for fuel treatments is practically restricted to FARSITE and FlamMap. The main advantage demonstrated by this study simulations was the identification of extreme fire hazard areas and the comparative assessment of the effectiveness of the alternatives available to decrease fire hazard.

Finally, it is important to recognize that southern Europe wildlands - where proactive fuel management is a necessity - differ from North-American and Australian wildlands. Smaller
size of forest patches, more variable land ownership and land management objective, marked heterogeneity in land uses and vegetation types and higher population density are factors that recommend the adoption of adjusted planning models and demand a critical analysis of decision-support systems outcomes.
C. CONCLUSÕES
6. Considerações finais

As alterações no uso do solo e no regime de fogo impelem os gestores florestais para uma abordagem da defesa da floresta contra incêndios delineada à escala da paisagem. O fogo controlado é uma ferramenta que pode ser utilizada para alcançar distintos objectivos de gestão, entre eles a protecção contra incêndios. A bibliografia sobre o planeamento do uso do fogo controlado ao nível da paisagem é muito reduzida, verificando-se que a maioria dos estudos disponíveis sobre as estratégias de planeamento de tratamento de combustível tem origem nos EUA e Austrália.

A fundamentação das opções de planeamento deve ser baseada nos objectivos a atingir. Na gestão de combustíveis o que se pretende é produzir alterações no comportamento do fogo de forma a possibilitar um combate aos incêndios efectivo e em condições de segurança, reflectindo-se numa diminuição da dimensão da área ardida. Não é previsível que as alterações no combustível detenham per se a propagação de um incêndio, mas podem diminuir o impacto do fogo nas áreas tratadas, aumentando a resiliência dos povoamentos florestais ao fogo.

Para maximizar estes efeitos os tratamentos devem repercutir-se à escala da paisagem, e deve ser assegurada a sua sustentabilidade ao longo do tempo. Sendo os recursos os escassos, é importante estabelecer a sua localização estratégica e conhecer os padrões de recuperação da vegetação. O conhecimento actual sobre a dinâmica da acumulação de combustível após tratamento é aceitável para vários tipos de vegetação na região do Mediterrâneo, mas a informação empírica sobre como a acumulação de combustível (ou tempo desde o tratamento) se traduz na eficácia do tratamento é bastante escassa. O efeito de tratamentos repetidos sobre a dinâmica de combustível e mudanças na estrutura e composição de combustível também é pouco conhecida.

A implementação dos tratamentos no terreno segue normalmente dois conceitos: tratamentos por faixas (aceiros ou corta-fogos) e tratamento em mosaicos dispersos. Os dois modelos devem ser conjugados. As faixas de tratamento podem servir de apoio à expansão dos tratamentos de combustíveis para as manchas dos povoamentos florestais, constituindo zonas de ancoragem para o uso do fogo controlado. A expansão dos tratamentos de uma rede de faixas para os mosaicos irá maximizar a redução do perigo de incêndio.

Precedendo a fase de planeamento, deve ser efectuado um diagnóstico da situação, através da avaliação do potencial de propagação do fogo na paisagem. Devem ser identificadas as zonas com maior perigo de incêndio e quantificado o comportamento do fogo associado. Após elaboração dos planos de gestão de combustíveis, estes devem ser testados através do mesmo procedimento. Os simuladores são a ferramenta natural para este tipo de avaliação.
C. CONCLUSÕES

O módulo de propagação do fogo do software Landlord é uma ferramenta simples que permite de prever o potencial de propagação superficial do fogo na paisagem com recurso à topografia (declive), vento e características elementares do combustível (continuidade e humidade). Baseando-se em informação limitada os resultados reflectem essa condicionante, expressando apenas a indicação das células afectadas e não afectadas, sem quantificação do grau (comportamento do fogo) ou temporização da propagação.

O software FARSITE mostrou ser mais completo, permitindo obter um conjunto de resultados que possibilitam uma caracterização do comportamento do fogo na paisagem e no tempo, nomeadamente intensidade da frente de fogo, velocidades de propagação, tempo de chegada da frente, comprimento de chama, etc. Os resultados, em forma de mapa são, compatíveis com a utilização de SIG ampliando a capacidade de análise dos resultados e incorporação no planeamento da gestão florestal. É mais exigente na informação que requer para as simulações. No entanto a crescente disponibilidade deste tipo de informação em formato digital não condiciona a sua utilização. É ao nível dos dados meteorológicos que deve existir maior cuidado na obtenção de previsões ou registos de qualidade.

A avaliação do perigo de incêndio e o planeamento do uso do fogo controlado na paisagem podem ser auxiliado pelo uso de simulador dando prioridade às situações mais perigosas, como consequência de combustíveis e topografia. Permitindo a identificação de áreas de risco extremo de incêndio e da avaliação comparativa da eficácia das alternativas para diminuir o risco de incêndio.

Este procedimento foi testado, utilizando informação relativa a duas áreas: Perímetro florestal do Entre vez e Coura, em povoamentos de pinhal bravo, e Serra do Marão, com áreas de matos predominantes.

Verificou-se que após o tratamento da carga de combustível em povoamentos de Pinus <i>pinaster</i> é eficaz na diminuição do potencial de propagação de incêndios num período de 3 anos, tendo como valor de referência uma intensidade da frente de 500 kW/m (limite para o combate directo com ferramenta manual). Restrições associadas à biodiversidade recomendam que o intervalo entre queimas não seja inferior a 5 anos.

Na monitorização do efeito dos tratamentos na estrutura espacial de distribuição das áreas de maior perigo foram aplicados índices utilizados na ecologia da paisagem. O índice de maior mancha (Largest Patch Index) e o índice de dimensão média da mancha (Mean Size Index) mostram-se apropriados para quantificar a continuidade das áreas não tratadas e o grau de fragmentação induzido pelos tratamentos.

Daqui resultaram algumas recomendações para optimizar o efeito do fogo controlado no espaço e no tempo. Estes resultados são significativos apenas se o objectivo principal do tratamento é a protecção contra incêndios e não são válidos para o comportamento do fogo associado a condições meteorológicas extremas.
Os tratamentos incidem nas manchas (talhões) de povoamentos de pinhal bravo na região NO.

A dimensão das parcelas tratadas não deve ser muito grande, ou seja, um valor máximo de tamanho deve ser atribuído a cada parcela individual para um determinado ano, tendo em conta que o período de 3 anos de eficácia deve ser seguido por um período de 2 anos sem tratamento (restrição). Verificando-se o aumento de perigo nestes dois anos, a limitação da dimensão assegura que as áreas com maior acumulação de combustível são de dimensão reduzida.

O tratamento de áreas contíguas em anos consecutivos também deve ser evitado, pelas mesmas razões. As parcelas queimadas em anos consecutivos, vão atingir o limiar do perigo antes da repetição do tratamento (figura 6-1) e dar origem a blocos de maior dimensão com maior acumulação de combustíveis.

Simulações de comportamento do fogo demonstraram que a implementação de áreas de tratamento com fogo controlado reduzem a percentagem de área percorrida por incêndios intensos, aumentando a proporção da paisagem onde o fogo apresenta valores de intensidade inferior a 500 kW/m. A aplicação do FARSITE à área de estudo do Marão evidenciou o efeito dos tratamentos na reprodução da propagação do fogo na paisagem, conferindo uma redução na área percorrida por fogo com comportamento extremo. Verificou-se ainda uma alteração na velocidade de propagação, que se reflecte no aumento da área ardida no tempo e favorece a contenção dos incêndios na fase inicial. Os valores da velocidade de propagação média e a intensidade da frente de fogo são reduzidas em 36% e 33%. A fração da bacia hidrográfica onde o ataque directo teria sido eficaz sofreu um aumento de 88%.

Figura 6-1. Exemplificação do efeito do tratamento em parcelas adjacentes em anos consecutivos.
O FlamMap é um simulador de comportamento do fogo com aplicação na selecção de locais de tratamento de combustível, sendo actualmente uma referência na matéria.

A análise dos resultados das simulações indicaram que o plano de tratamentos de combustíveis para a Serra do Marão é eficaz na diminuição do potencial de incêndio florestal em larga escala, reduzindo a taxa de crescimento e aumentando a probabilidade de sucesso dos meios de supressão. Revelou no entanto alguns problemas conceptuais no projecto, que recomendam a expansão da largura de algumas faixas e um maior grau de sobreposição entre faixas de gestão de combustíveis sucessivas. Como os resultados reflectem o primeiro ano de execução do projecto propõem-se que, no futuro, evolua para um mosaico de tratamentos de combustível, uma abordagem mais eficiente e complementar à criação de uma rede de faixas de gestão de combustíveis.

A simulação espacial da propagação e comportamento do fogo é uma ferramenta poderosa para analisar cenários alternativos de gestão de combustível. O resultado da simulação do comportamento do fogo para a proposta de optimização FlamMap foi semelhante ao do plano de tratamentos para fogo controlado.

O modelo de faixas de gestão de combustíveis (uma estratégia de gestão de combustível baseada no isolamento) é prática generalizada no sul da Europa. A largura destas faixas, em alguns casos, verificou-se ser reduzida, mas a sua elevada densidade na implantação no terreno, pode conduzir a uma aproximação à estrutura de tratamento de combustível com elevado grau de sobreposição (Finney 2001). A topologia do plano de fogo controlado do Marão apresenta semelhança com a sobreposição completa do modelo, especialmente no caso do cenário de incêndio com ventos de SE. Era evidente alguma sobreposição entre as duas propostas (os tratamentos da simulação e tratamentos implementados), e considerando que a percentagem de área tratada é baixa, pode ser aconselhável para optimizar ainda mais o padrão espacial, combinar os vários cenários.

Uma deficiência óbvia do processo de optimização do tratamento é a ausência de uma opção para ancorar tratamentos (por exemplo, vias de acesso), que é muito importante nas operações de fogo controlado.

Finalmente, é importante reconhecer que as áreas florestais sul da Europa - onde a gestão pró-activa de combustível é uma necessidade - diferem das norte-americanas e australianas. Menor dimensão da propriedade florestal e falta de gestão florestal, elevada heterogeneidade dos usos da terra e tipos de vegetação e maior densidade populacional são factores que recomendam a adopção de modelos de planeamento ajustados e uma análise crítica dos resultados dos sistemas de apoio à decisão. Aconselha-se o uso de simuladores para implementação e planeamento dos tratamentos, mas complementado com o conhecimento e experiência local dos gestores, num processo dinâmico de validação e actualização, fase ao cumprimento dos objectivos estabelecidos e à inevitabilidade da ocorrência de incêndios nas áreas abrangidas pelos planos.
C. CONCLUSÕES

Tabela 6-1. Esquema de delineamento para planeamento estratégico de gestão de combustíveis com recurso a simuladores de comportamento do fogo

<table>
<thead>
<tr>
<th>Cartografia temática da área</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MDT</td>
<td></td>
</tr>
<tr>
<td>Carta de declives</td>
<td></td>
</tr>
<tr>
<td>Carta de exposições</td>
<td></td>
</tr>
<tr>
<td>Carta de combustíveis</td>
<td>Cenário sem tratamentos</td>
</tr>
<tr>
<td>Cartas dos povoamentos florestais</td>
<td></td>
</tr>
<tr>
<td>Coberto</td>
<td>Cenário sem tratamentos</td>
</tr>
<tr>
<td>Altura</td>
<td></td>
</tr>
<tr>
<td>Base da copa</td>
<td></td>
</tr>
<tr>
<td>Densidade da copa</td>
<td></td>
</tr>
</tbody>
</table>

| Dados meteorológicos       |  |
| Séries temporais:          |  |
| Temperatura                |  |
| Humidade Relativa          |  |
| Ventos (Vel./Dir.)         |  |

<table>
<thead>
<tr>
<th>Simulação para diferentes cenários</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>FARSITE</td>
<td>Histórico de incêndios</td>
</tr>
<tr>
<td>FLAMMAP</td>
<td>Perigo de incêndio na paisagem</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Simulação de localização dos tratamentos FLAMMAP</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ajustamento da proposta FLAMMAP com rede viária, caminhos e aceiros implementados, e ajustamento da dimensão das parcelas</td>
<td></td>
</tr>
<tr>
<td>Carta de combustíveis com parcelas de tratamento</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Validação</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulação com cenário ajustado</td>
<td>comparação com cenário pré-tratamento</td>
</tr>
<tr>
<td>Plano de tratamentos e calendarização</td>
<td></td>
</tr>
<tr>
<td>Ajustamento anual do plano de tratamentos</td>
<td>Parcelas tratadas + Incêndios</td>
</tr>
</tbody>
</table>

|  |  |
| Simulação da evolução durante o período calendarizado |  |
Bibliografía


Agradecimentos

Em Setembro de 1997 tive o prazer de integrar o Grupo de Fogos da UTAD e desde essa data ter trabalhado com algumas das mais importantes pessoas que neste país e fora dele impulsionam a mudança de ideias e atitudes fase ao fogo florestal. No final deste período de aprendizagem de que resultou esta Tese de Mestrado, quero agradecer:

Ao Professor Hermínio Botelho, por me ter proporcionado a oportunidade de trabalhar com os melhores, pela orientação nesta tese de mestrado, pelas várias oportunidades de trabalho ao longo destes anos, e por sempre ter assegurado a manutenção de condições de trabalho dignas, no meio da instabilidade associada ao trabalho na área da investigação.

Ao Investigador Paulo Fernandes, Colega, Amigo, Conselheiro, Orientador e verdadeiro responsável por os trabalhos aqui apresentados terem sido apresentados para publicação. O futuro do Grupo de Fogos é ele.

Ao Professor Francisco Rego, pelos conselhos, oportunidades de trabalho e aprendizagem que me proporcionou

Ao Professor João Bento pelos “empurrões“ para que este trabalho visse a luz do dia.

À Doutora Manuela Ribeiro, que através da Sociologia me abriu uma porta de entrada no mundo do fogo florestal.

Aos colegas do Grupo de Fogos e do Departamento Florestal UTAD: Délio Sousa, Natália Baptista, Filipa Torres, Emília Silva, Manuel José Fernandes, ... (tantos que não cabem todos). Obrigado pela camaradagem e apoios ao longo de muitos anos.

Aos projectos financiados pela Comissão Europeia:

FIRE TORCH - Prescribed Burning as a tool for the Mediterranean Region: a management approach. Project ENV4-CT98-0715/DGXII/EC

ModMED - Modelling Vegetation Dynamics and Degradation in Mediterranean Ecosystems. Project ENV4-CT97-0680/DGXII/EC

Fire Paradox, contract n° FP6-018505, Integrated Project financially supported by the European Commission under the 6th Framework Programme priority 6 - Sustainable Development, Global Change and Ecosystems.

que contribuíram financeiramente para a realização dos trabalho, do intercâmbio de experiências e da descoberta de outras realidades.

À minha Catarina, que me atura à 25 anos...