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XX CICLO

FIRE BEHAVIOUR SIMULATION IN MEDITERRANEAN MAQUIS USING FARSITE (FIRE AREA SIMULATOR)

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A babbo, mamma e Vincenzo

"All models are wrong. Some are useful."
- George E. P. Box

"No amount of experimentation can ever prove me right; a single experiment can prove me wrong."
- Albert Einstein

ABSTRACT

In the last two decades several simulation systems were developed to provide information about temporal and spatial variations of fire spread and behaviour. FARSITE (Fire Area Simulator), one of the most common simulators, is a spatially and temporally explicit fire simulation system. The simulator is based on Rothermel's fire spread model, and describes the fire spread and behaviour as a function of relationships among fuels, topography and weather conditions. The use of FARSITE on areas different from those where the simulator was originally developed requires a local calibration in order to produce reliable results. This is particularly true for the Mediterranean ecosystems, where plant communities are characterized by high specific and structural heterogeneity and complexity, determined by the interaction of sub-arid Mediterranean climate and human factors. Therefore, to perform FARSITE calibration, the choice of the appropriate standard fuel models or the development of specific custom fuel models are required. In addition, the capabilities of FARSITE simulator can be affected by other environmental characteristics, as complex steep terrains with the resulting high spatial and temporal variability of wind speed and direction.

In this work, FARSITE was employed to simulate spread and behaviour of four real fires occurred in North Sardinia during 2003, 2004 and 2006 summer seasons. The effect of fuel models, weather conditions and topography on the accuracy of FARSITE simulations was evaluated in order to assess the capabilities of the simulator in accurately forecasting the fire spread and behaviour in areas covered by Mediterranean maquis. A custom fuel model, designed and developed by our working group for maquis, provided realistic values of simulated fire behaviour. Improvements on the accuracy of both fire spread and behaviour were also obtained using raster maps of wind speed and direction. The results confirm that the use of both accurate wind field data and appropriate custom fuel models is crucial to obtain accurate simulations of fire behaviour occurring on Mediterranean vegetation during the drought season, when most wildfires occur.

RIASSUNTO

Negli ultimi venti anni sono stati sviluppati diversi sistemi di simulazione col fine di studiare le variazioni spaziali e temporali della propagazione e del comportamento degli incendi. FARSITE (Fire Area Simulator), uno dei simulatori più diffusi, è in grado di fornire previsioni del comportamento e dell'evoluzione dell'incendio nel tempo e nello spazio. Il simulatore è basato sul modello di propagazione di Rothermel, e descrive il comportamento e l'avanzamento di un incendio in funzione delle interazioni fra vegetazione, topografia e condizioni meteorologiche. L'impiego di FARSITE in aree diverse da quelle in cui il simulatore è stato originariamente messo a punto richiede una calibrazione locale affinché si possano ottenere risultati attendibili. Quanto affermato è in particolar modo valido per gli ecosistemi mediterranei, in cui la comunità vegetale è caratterizzata da un'elevata eterogeneità e complessità specifica e strutturale, determinata dall'interazione fra clima mediterraneo sub-arido e fattori antropici. Pertanto, per la calibrazione di FARSITE è necessario ricorrere alla scelta dei più appropriati modelli di combustibile standard oppure sviluppare dei modelli di combustibile specifici per le condizioni vegetazionali locali. Inoltre, le potenzialità del simulatore FARSITE possono essere influenzate da altre caratteristiche ambientali, quali condizioni orografiche particolarmente complesse, in grado di indurre un'elevata variabilità spaziale e temporale delle condizioni anemometriche.

In questo lavoro, FARSITE è stato utilizzato per simulare la propagazione e il comportamento di quattro incendi verificatisi nel nord Sardegna durante le stagioni estive 2003, 2004 e 2006. E' stato studiato l'effetto dei modelli di combustibile, delle condizioni meteorologiche e della topografia sull'accuratezza delle simulazioni condotte in aree a macchia mediterranea. Un modello di combustibile adattato alle suddette condizioni vegetazionali ha fornito valori maggiormente realistici del comportamento degli incendi simulati. Un miglioramento nell'accuratezza delle simulazioni del comportamento e della propagazione degli incendi è stato inoltre ottenuto impiegando mappe della velocità e della direzione del vento. I risultati confermano che l'uso di dati anemometrici accurati e dei modelli di combustibile appropriati è cruciale per l'ottenimento di accurate simulazioni del comportamento degli incendi che interessano la vegetazione mediterranea durante la stagione arida, nella quale si concentra la maggiorparte degli incendi.

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INTRODUCTION

The European territory is covered by about 1,000 million hectares of forest, about one half of its whole surface. Europe has been divided in eleven bio-geographical regions (Alpine, Anatolian, Artic, Atlantic, Black Sea, Boreal, Continental, Macaronesian, Mediterranean, Pannonian, Steppic). In these regions the main forest categories are: Western Taiga, Oak and Beech Forests, Deciduous Mediterranean Forests, Sclerophyllous Mediterranean Forests, Temperate Mountain Conifer Forests, Mediterranean and Macaronesian Mountain Conifer Forests (European Commission, 2003). The Euro-Mediterranean region is one of the most important in terms of biodiversity. In this part of Europe, situated in a transitional zone among the European, African and Asian continents, 25,000 floral species (approximately 10% of the world flowering plants) are present. The Mediterranean ecosystems are the biomes of some regions of the moderate-warm belt, with a climate conditioned by seas and oceans: this climate represents a transitional regimen between moderate and tropical-dry climates (Di Castri and Mooney, 1973). The Mediterranean climate presents a marked seasonality. During the year, a fresh and rainy period alternates with a warm and dry season of variable length; between these two seasons, two periods with intermediate characteristics are present. The annual medium temperatures range between 14 and 20 °C (Pignatti, 1995). The minimum temperatures come down very rarely under 0 °C during winter, and snowy precipitations and frosts have limited incidence. In summer the maximum temperatures are lower than 50 °C. Seas and oceans exercise a meaningful mitigating effect on the thermal regimen, so the range of temperatures is modest regarding continental climates (Bussotti and Schirone, 2001). The precipitations, concentrated in the winter period, reach annual values ranging from 250 to 1300 mm; in the warm season the rainfall is poor, or almost null. However, there is a high variability among years as for the annual values of precipitations. These climatic conditions characterise five different regions of the world: the Basin of the Mediterranean Sea, California in the United States, the central zone of Chile, South Africa and south-western Australia (Specht, 1969). The above mentioned areas occupy little more than 1% of emerged lands, and most of this amount are located in the Mediterranean Basin. The Mediterranean climate and ecosystems are concentrated mainly in the western areas of the continents, in correspondence with a belt of 15 ° (approximately) around the 35 ° parallel, in both the boreal and austral hemisphere.

The Mediterranean climate is the main factor determining the characteristics and the dynamics of the Mediterranean vegetation. The Mediterranean environment presents a very heterogeneous vegetation, constituted, in wide measure, by evergreen forests and characterized by the dominance of evergreen shrubs, with broad and small, stick and thick leaves (sclerophyill) (Di Castri, 1981; Bussotti and Schirone, 2001). Such shrub formations are locally called *macchia* in Italy, *maquis* in the francophone Countries and Israel, *matorral* in Spain and Chile, *chaparral* in California, *mallee* in Australia, *strandveld* (on dunes) and *renosterveld* in South Africa (Di Castri, 1981; Gaudenzio and Peccenini, 2002). When the shrub vegetation is low and poor, along gradients of increasing aridity, the term becomes *gariga* in Italy, *garrigue* in the francophone regions, *phrygana* in Greece, *batha* in Israel, *coastal sage* in California, *jaral* in Chile. The term *fynbos* indicates instead South Africa vegetation dominated by Erica. By considering the variability of some climatic and geo-morphologic factors of the Mediterranean environment, it is not useful to consider just one representative ecosystem: this fact represents a big difference with respect to other zones, in which environment and vegetation are uniform. Therefore, when the Mediterranean biome is considered, we make reference to a whole of ecosystems, each one occupying habitats with peculiar environmental conditions.

In an ecosystem, the maximum degree of development and equilibrium the vegetation community can reach is named climax: the climax is reached after a sequence of changes in the ecosystem (succession). Following an increasing order of altitude, in the Mediterranean zones five climax vegetations can be distinguished: Coastal Zones Climax, Oleo-Ceratonion, Mediterranean Maquis, Mediterranean Evergreen Forest, Mediterranean Deciduous Forest. A considerable portion of the Mediterranean natural ecosystems is occupied by Oleo-Ceratonion, Mediterranean Maquis and Mediterranean Evergreen Forest climax, and also by secondary vegetation formations. The secondary formations are associations of vegetation deriving from climax, and in dynamic state of degradation or evolution towards a climax formation. Among these secondary formations, gariga, steppic grassland and secondary maquis (which can assume different characteristics in relation with prevailing species) can be mentioned. The secondary maquis represents an involutional stage of the Mediterranean shrubland, which can evolve and originate Oleo-Ceratonion, Mediterranean Maquis, or Mediterranean Forest, in relation with environmental conditions and vegetation characteristics.

The Mediterranean ecosystems are very vulnerable, with respect to other vegetation typologies: many causes can lead these ecosystems to degradation. Several Mediterranean zones have characteristics and environmental conditions particularly favourable to the human presence and activities: these aspects facilitated the urbanization. Moreover, considering the natural beauties and the mild climate, in many zones a flourishing tourist activity increased. The urbanization and the increment of population involved an increase of the human productive activities, with a remarkable expansion of commercial and industrial activities and of means of communication. An intensive agriculture developed, with the aim to produce large amounts of vegetables and fruits on relatively modest areas, with a consequent strong exploitation of lands and a massive consumption of resources (energy, water, etc.). The effect of the overgrazing pressure influenced various regions, with changes in the vegetation distribution models and in the landscape dynamics. The overgrazing, linked with fires, accelerated the erosion problems in steep landscapes and in areas with low vegetation, with an important reduction of the soil fertility and of the forested areas (Luciano and Franceschini, 2006). On the contrary, in those regions which are more distant from sea and towns, some studies pointed out the progressive abandonment of agriculture and the reduction of the environment management. All these factors induced in the years a progressive degradation of the Mediterranean ecosystems. Since the Mediterranean vegetation has always been subject to recurrent fires (Naveh, 1975), mostly of anthropic origin, wildfires can be considered as a natural environment element. Some Mediterranean species “forged” and evolved acquiring resistance to fire, and others even “need” occasional fires to survive. Unfortunately, at present wildfires represent one of the main threats that the Mediterranean ecosystems must face: wildfires are usually the main destruction cause for the Mediterranean forest environment (Velez, 2000).

In the dry season the fire propagation is favoured by warm-dry meteorological conditions, with the resulting high degree of flammability of the vegetation; the wind intensity also plays a relevant part in fire spread and behaviour. In the last years (2000-2005), in the South-Western European Mediterranean region (Italy, France, Spain, Portugal, Greece) more than 60,000 wildfires per year have been recorded, with about 490,000 hectares of burned areas (European Commission, 2006). During the past 2007 summer season many European Countries experienced disastrous wildfires. In Greece, the overall burned area in 2007 amounted approximately to 270,000 hectares, of which 180,000 burnt between the 24 and 30 August (European Civil Protection, 2007); during these days more than 60 people died. Also in Italy last summer fire season provoked many damages, with 230,000 hectares of burned areas mainly concentrated in the southern part of the Country (Corpo Forestale dello Stato, 2007a; 2007b).

Also Sardinia must face the wildfire problem each summer season: on average, during the period 1971-2005, in our island 3,000 wildfires per year have been recorded, and 41,000 hectares of natural landscapes have been burned (Boni, 2004). But, in the last years (1996-2005), on average the number of fires per year decreased until 2,700 and the burned areas until 18,000 hectares. Most wildfires are linked with human activities, both for intentional and accidental causes. For example, during the 1994-2003 summer seasons in Sardinia only 1% of the observed wildfires was not linked with human activities, and the arson number ranged between 65-85% of the fires (Saba, 2004). In the Mediterranean areas, up to 95% of fires have anthropic origin, both for arson and negligence (FAO, 2007). Some interannual fluctuations in this phenomenon can be observed, particularly due to the increase of the extreme fire seasons related with the pattern of summer meteorological conditions. Therefore, wildfire remains a serious problem, even if the average burned area per fire has decreased in the last years.

Every year wildfires cause a devastating damage for the natural environment and ecosystems, sometimes also destroying houses and farms and causing casualties and death. If wildfires are recurrent, it is possible to observe a gradual destruction of the structure and of the floristic composition of the vegetation, with the appearance of more degraded vegetation formations characterized by involutional dynamics that can bring to landscape desertification. Moreover, in those regions where tourist activities prevail, the loss of natural areas determines an impoverishment of the landscape, the loss of important natural forest areas, and it risks to inflict serious damages to the image of the Mediterranean regions, making useless all the efforts for tourist promotion and development. Since the European Mediterranean region is considered as one of the most important regions in the world for its biodiversity features, it should be very important to increase the efforts in order to limit the hectares of forests and other wooded lands annually destroyed by fires.

In order to face the wildfire calamity, the European Union, the Countries and the regional and local Administrations annually assign huge financial resources in order to guard, to monitor and to fight wildfires: the main part of the efforts against wildfires is circumscribed to the active fight. In the last ten years, the strengthening of the wildfire contrast action (strong technological development and modernization, introduction of more flexible and effective aerial craft, growth of terrestrial forces, etc.) permitted to obtain a meaningful benefit, with an important reduction of the burned areas in many Mediterranean regions. For example, in Sardinia the increased efficiency of the firefighting apparatus allowed to have 92% of fires up to 10 ha, and 60% of fires less than 1 ha (Boni, 2004).

Unfortunately, the active fight apparatus sometimes is unable to respond to all the intervention demands, when severe environmental conditions lead to an increase of wildfire frequencies. In these situations, wildfires can become unmanageable, burning wide areas and bringing serious damages in the landscape.

The use of decision support systems (DSSs) can be useful in the optimization of resources, in order to decide the priority of the aerial and terrestrial interventions, considering the site characteristics: presence of residential zones, fires threatening relevant natural interest areas, adverse meteorological conditions, presence of particularly vulnerable vegetation, etc.. DSSs can be also used for the development of fire prevention and management policies, to reduce the wildland fire risk. A DSS can be developed incorporating fire spread and behaviour prediction models, geodatabases of environmental and vegetational information, as well as sets of decision rules.

As for prediction models, fire spread and behaviour can be simulated using semi-physical or empirical models developed over recent years. Among these wildfire behaviour modelling systems, FARSITE (Fire Area Simulator; Finney, 1994) represents one of most complete and user friendly model in order to study ignition, propagation and behaviour of fires: FARSITE is capable to consider the aerial and terrestrial interventions against fire during the event. FARSITE, like most fire prediction models, has been calibrated and validated in the United States, or in ecosystems different from the Mediterranean Basin ecosystems. The fire behaviour and propagation is a very critical topic for a decisive intervention, since the fire is an event with highly variable evolution (in time and in space) and with dynamic characteristics, especially with heterogeneous types of vegetation and with severe meteorological conditions. Therefore, an extensive calibration and validation of these models is required in order to obtain reliable results on Mediterranean vegetation. The other research demand is represented by the reconstruction of the wind fields, which constitute the greatest element of variability during a fire.

The Italian Presidenza del Consiglio dei Ministri, with the Dipartimento della Protezione Civile (2002) (Gazzetta Ufficiale, February 26, 2002, n° 48), promoted most of the approaches and strategies mentioned in this introduction section, by the legislative decree December 21, 2001, which states that the most useful approach in order to pursue the conservation of the forest lands is linked with the promotion and the stimulation of the prevention and forecast activities, rather than privilege only the emergency phases of wildfire extinction (…). To obtain a constant and radical reduction of the causes of wildfire ignitions, the use of forecast systems is important to localize and study the fire danger characteristics or to adopt initiatives of prevention, in order to realize an organic management of interventions and actions to mitigate the wildfire consequences (…). The decree also emphasizes the role of survey techniques from satellite images, GIS applications, and the modelling approach in order to produce simulations of the fire behaviour.

The Department of Economics and Woody Plant Ecosystems, University of Sassari, in collaboration with the Institute of Biometeorology, National Council of Research of Sassari, have developed a series of research activities in order to strengthen the fire risk management and to predict the spread and behaviour of fires. In the specific instance, the main topics have been the evaluation of the meteorological condition effects on vegetation, the development of a fire risk dynamic model (Ichnusa Fire Index) (Pisanu, 2005; Spano et al., 2005; Sirca et al., 2005) and the calibration and validation of a fire behaviour model (FARSITE) for Mediterranean areas.

This work focuses on the evaluation of the capabilities of FARSITE simulator in order to model the fire spread and behaviour on historical fires observed in the Mediterranean maquis of Sardinia and on the analysis of the effects of weather conditions, vegetation and topography on the simulations.

FIRE BEHAVIOUR DESCRIPTION

A wildfire is an uncontrolled fire occurring in wildland areas, but it can also involve urban or agricultural areas. The term fire behaviour is used to describe magnitude, direction and intensity of the fire spread. The wildfire behaviour is generally defined by considering the ways the vegetation burns, the flames develop, the fire spreads and manifests extreme behaviours (for example firewhirls, spotting, etc.). The fire behaviour is widely linked with meteorological conditions of short, medium and long time, with physical conditions (local and regional topography and landscape characteristics) and with vegetation (Countryman, 1972; Rothermel, 1983; Pyne et al., 1996; DeBano et al., 1998). Since the combinations among these elements are almost infinite, and since the ignition point is not predictable, the wildfire growth and behaviour have univocal characteristics (Graham et al., 2004).

Really, during a fire it is not usual to record just one behaviour, but there are several variations of the wildfire behaviour on temporal and spatial scale, because of the different and changing environmental conditions. Various useful characteristics can be used to describe the wildfire behaviour: among the most important, we can mention rate of spread, fireline intensity, flame height, transition to crown fire. As described later, these elements are modelled and measured in the advanced front of the fire (heading fire), but they can also be estimated for every direction in which the fire spreads. In addition to the cited elements, one of the most used and immediate parameters for the description of the wildfire behaviour is the burned area (Rothermel, 1991).

1. Combustion and Heat Transfer

Combustion. The contemporary presence of three primary elements is necessary for a fire to develop: heat, oxygen and fuel. These components define a very common diagram, named "fire fundamental triangle" (Figure 1).

Figure 1. The fire fundamental triangle

The vegetation burns only in particular conditions, after receiving a sufficient amount of heat, and reacts with the atmospheric oxygen releasing combustion by-products (water vapour, carbon dioxide, particles, ashes, etc.) and generating heat in its turn. In an ecosystem, the fuel is represented by the organic matter of the vegetation; the fuel, in presence of oxygen and heat, supplies the chemical energy for the fire propagation (DeBano et al., 1998). The heat refers to the initial source of energy imparted to the fuel and necessary to carry the vegetation to the ignition temperature, but also to the energy released during the combustion: for a fire to continue to burn, this energy must be transferred from fire to unburned vegetation. The heat flow can happen according to four modalities: radiation, convection, conduction, mass transport. The oxygen is the third component of the fire triangle, and generally it is always available in natural ecosystems. This gas is indispensable because it represents the oxidant agent of the combustion reaction, thanks to which the chemical energy stored in the plants is released in the atmosphere.

The combustion is a rapid chemical-physical process and it can be defined like the inverse process of photosynthesis (Pyne et al., 1996; DeBano et al., 1998). The process of combustion follows a definite sequence, apart from the type of burned vegetation: the chemical energy stored in plants is released in form of heat, several gases and particles with different dimensions. The combustion process can be represented with the following equation:

$$(C_6H_{10}O_5)_n + O_2 + INITIAL\ HEAT \rightarrow CO_2 + H_2O + HEAT \qquad (1)$$

Initially the reaction is endothermic, later it becomes exothermic.

The combustion process can be divided at least into four phases (Pyne et al., 1996; DeBano et al., 1998): pre-ignition; ignition; combustion (flaming, smoldering and glowing); extinction.

The first phase of the combustion process is the *pre-ignition*, in which a pilot source provides the heat needed to raise fuels to the temperature range (325-350 °C) needed for ignition (DeBano et al., 1998). Because of the increment of the fuel temperature, the free water of plants progressively evaporates (dehydration). As fuels are heated by radiation and convection to temperatures greater than 100 °C, water vapour, noncombustible organics and volatile extractives are distilled to the fuel surface and driven off into the air (Ryan and McMahon, 1976). As soon as caught up elevated temperatures, the pyrolysis can start: it represents the thermal degradation of the fuel (DeBano et al., 1998), by which the long polymer chains are divided in gaseous molecules with low molecular weight, in semi-volatile carbonic tars and in solid chars. During pre-ignition, a limited amount of smoke, in prevalence white-coloured, and constituted mainly by water vapour, is produced.

The *ignition* is the phase between pre-ignition and combustion, and it defines the transition point between endothermic and exothermic phase of combustion. To this point the fire is able to self-sustaining, since the heat produced by the combustion provides the energy needed for the pre-ignition of the unburned fuels, allowing the prosecution of the combustion process.

The following phase of *combustion*, in its turn, can be sub-divided in three sub-phases: flaming, smoldering and glowing.

During the *flaming combustion*, the products of pyrolysis, mainly combustible gases and vapours, mix with oxygen, and burn during the flaming part of combustion. Temperatures exceeding 1650 °C have been measured in exceptionally intense fires, but flame temperatures of 700-980 °C are more common (Pyne et al., 1996). The heat produced from the flaming reaction accelerates the pyrolysis rate and releases greater quantities of combustible gases (DeBano et al., 1998). The smoke rises up by heat action, and it is prevalently constituted by carbon dioxide and water vapour. The flaming combustion is initially vigorous; it reduces its vigour when the charcoal formation on the surface of woody fuels reduces the fuel thermal conductivity and the flux of heat deep into the burning wood (DeBano et al., 1998). To this point, the chars can burn as a result of superficial oxidation process, by means of smoldering combustion or glowing combustion.

The *smoldering combustion* is a sub-phase in which combustion is without flames. It happens when the production of combustible gas decreases and the vigorous combustions are not possible, with a consequent drop of temperatures and released heat. Larger amount of gases condense into smokes, and the maximum particulate emission is recorded. The presence of particulates confers a darker colour to smoke, compared to previous phases.

The *glowing combustion* is the last part of combustion. In this sub-phase, volatile gases are no more produced and atmospheric oxygen comes into direct contact with surface of the charred fuel. As a fuel oxidizes, it burns with a characteristic glow and continues this process until the temperature drops so low that combustion can no longer occur or until the fuel is reduced to noncombustible ashes (DeBano et al., 1998). Because of this, there is no production of smoke.

The *extinction* represents the final phase of the combustion process. A fire goes out when all the fuel is consumed or when the heat is not sufficient to support neither combustion nor pyrolysis.

Heat Transfer. The heat produced during a fire is transferred to the different components of the ecosystem by four processes: radiation, convection, conduction, mass transport. Among these processes, radiation and convection are the most common mechanisms by which heat is transferred from a fuel to another fuel. Large amounts of heat are lost into the atmosphere along with smoke, gases, particulate matter generated by fire. It has been estimated that only 10-15% of the heat energy released during the combustion of aboveground fuels is absorbed and directly transmitted to litter and duff or mineral soil (DeBano, 1974; DeBano et al., 1998). The transfer of heat through mineral soil is very important because it is the main responsible for the changes in the physical, biological and chemical properties of soil.

Radiation represents the heat transfer by the movement of electromagnetic waves, that travel at the speed of light. Therefore, radiation represents the transfer of heat from one body to another (not in contact with it) by electromagnetic waves motion. Fire is a remarkable source of radiative energy, since flames can reach 1400 °C and the temperatures in the combustion zone can reach 1000-1200 °C. Applying Stephan-Boltzmann's* law, the amount of energy released by a body in combustion can be calculated: since the energy is proportional to the fourth power of the temperature of the radiant body, radiation is a very important process during wildfires. In general, radiation is typically the major mode of heat transfer during the advance of a fire in still air (DeBano et al., 1998); it is moreover the primary mechanism of heat transfer during the initial stages of many forest fires (Chandler et al., 1983).

Convection is the process whereby the heat is transferred from a point to another by the mixing of fluid masses (Chandler et al., 1983; DeBano et al., 1998). Two main modalities of convection can be distinguished: free and forced convection. Free convection is when the fluid motion of gases only depends on differences in densities, resulting from temperature differences. The formation of the convection column (smoke plume) or the heating of shrub and tree crowns above a surface fire are examples of heat transfer by free convection (DeBano et al., 1998). Forced convection occurs when external mechanical forces alter the flows of fluids from their "natural and free" velocity and direction (Chandler et al., 1983): wind can act as external mechanical factor. In conditions of strong external convective forces, as for example intense winds, the main process of heat transfer from the burning fuels is the convection (DeBano et al., 1998).

Conduction is the heat transfer between two bodies in contact, by means of the increment of the molecular activity. Since air, soil, wood and water conduct heat slowly, conduction does not have a meaningful importance during a fire.

Mass transport is the process of heat transfer tied to spotting and downslope rolling. Spotting involves the physical removal of burning material by thermal updrafts from flaming fuels and the subsequent deposition in unignited fuels after a flight of

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* $E = \sigma \times T^4$, E = energy produced by the body (W m^{-2}), σ = 5,67 x 10^{-8} W m^{-2} K^{-2}, T = body temperature (K).

various meters (some kilometres are not rare) (DeBano et al., 1998). The fuel able to move by spotting is constituted in prevalence by particles with modest weight. Downslope rolling is important on steep slopes, being tied to the gravitational forces which can move burning conifer cones, logs, twigs or branch downslope into unburned fuels, and therefore promoting the ignition of new fires in the downstream zones.

2. Environmental Conditions and Fires

The fire behaviour is a product of the environment in which the fire is burning (Pyne et al., 1996). Countryman (1972) presented the concept of the fire environment: the fire environment is represented by the surrounding conditions, influences, and modifying forces that determine the fire behaviour. The interacting forces and influences that constitute the fire environment are represented by topography, weather, fuel and the fire itself. The fire environment triangle (Figure 2) illustrates this concept. It is called triangle because three components, and the interactions among them and fire, affect the fire spread and behaviour (Rothermel, 1983, Pyne et al., 1996). The fire in the center of the triangle symbolizes the interaction between fire and environment.

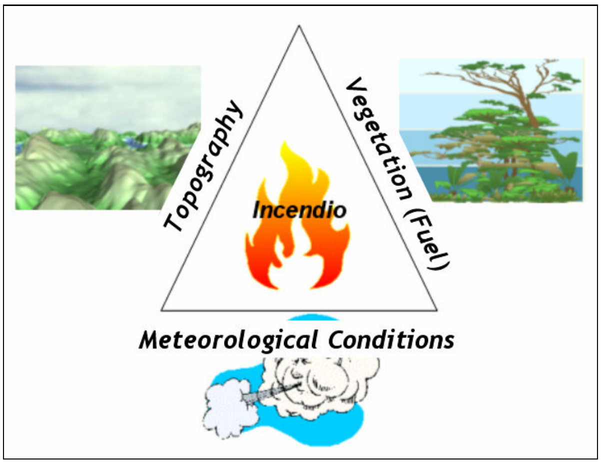

Figure 2. The fire environment triangle (from Countryman, 1972)

It can be point out that:

- topography can change strongly in space, but not in time;
- vegetation changes in space and in time;
- meteorological conditions represent the most changing component, with fast and often meaningful variations in space and time.

There is a fourth factor, frequently ignored but fundamental in order to describe the fire behaviour (Viegas, 2005a): the time. Really, the wildfire behaviour is dynamic, and all the spread characteristics can change during the time, even if the environmental conditions are unchanged. Considering the time variable, the "Square of the Fire Environment" can be used.

2.1. Topography

Topography is a static element, since it cannot change in time but only in space; although that, it strongly influences weather and vegetation, besides the fire behaviour (Pyne et al., 1996). The effect of the topography on fire is marked in zones with complex orography, while it tends to be limited in flat areas.

Slope is the topographical element that mainly influences the fire propagation. First of all, the slope affects an important meteorological phenomenon on local scale. In ridges, the air masses heated by sun, with low density, go up towards the survey top, and originate a draft, which moves upslope (during the night the air flow moves in the opposite direction). Therefore, in a ridge it is usual to observe the movement of warm air masses along the slope, during diurnal hours: this is the reason why a fire often spreads easily along the line of maximum slope. The more elevated the slope is, the faster and more intense the fire spread and growth are. Flames, moving along the slope, are facilitated in combustion. As the fuelbed is tilted, the distance between the flame and an unignited fuel particle ahead of the flame decreases: consequently, more radiative energy reaches the same fuel particle in tilted fuelbed in comparison to the level fuelbed. This results in more rapid heating of the fuel particles and in faster rate of spread (Morais, 2001). Since during the fire remarkable amounts of heat are released, the movement of warm air masses is more emphasized, and in its turn the growth of the speed of air masses increases the fire rate of spread. Therefore, during the day, a fire that moves upslope tends to "feed on itself" and to accelerate progressively its rate of spread till the top of the relief (Viegas, 2006). The wildfires in these conditions become rapidly extensive, and sometimes they are controllable only when the top of the ridge is reached: here the fire will face an opposite direction air flow coming from the other side of the relief. The combined effect of slope and warm air flows can originate a very dangerous phenomenon for Firefighters, named *chimney effect*; it is common in terrain with steep sides and in canyons (Pyne et al., 1996). In these zones, the upslope air flows is rapid and funnelled to the chimney's shape; these chimneys draft a fire like a stove chimney. The fast acceleration of a fire in areas with steep sides and in canyons can remember an eruption, so we can also speak of *eruptive behaviour* (blowup is the term commonly used by northern American researchers) (Viegas, 2005b; Viegas et al., 2005; Viegas, 2006).

Elevation influences the general climate and therefore the fuel availability. Although the effect of the elevation above sea level is often mentioned for its relation with air temperature, rainfall and atmospheric oxygen content, the effective incidence of this element on fire behaviour is somewhat limited (Velez, 2000).

Aspect is the direction in which the side of a topographical relief is facing regarding the cardinal points. There is a relation between orientation of a side and amount of solar radiation: south and south-west facing slopes receive more direct sunlight (and more radiation) and are therefore warmer than the north facing slopes (Pyne et al., 1996; Velez, 2000). The aspect of a relief is also important because it influences the exposure to predominant winds.

Landscape configuration influences the wind direction and movement. For example, the mountain chains represent a barrier to the horizontal movement of the air masses. The wind is deviated as soon as it arrives in proximity of chains, as result of the action of local convective winds moving along the maximum slope of the slide. The airflows, in their movement towards the top, can arrest or limit a fire, when the flames arrive on the highest parts of a relief. Ravines and gullies form privileged ways for the movement of air masses and can modify the fire spread direction. In tight gully, the heat released by a fire causes the loss of humidity and the consequent drying process of the vegetation on the opposite side. When the air flow is "trapped" by topography, it tends to increase its speed, with an increase of both the fire intensity and the spread rate.

Barriers are elements, natural or artificial, able to oppose or slow down the fire propagation. A barrier cannot support wildland fires because the fuel is not present. Using the description of Scott and Burgan (2005), in the group of barriers the following elements are present: urban or semi-urban areas; zones with ice or snow; some agricultural areas (ploughed field, rice field, etc.); open bodies of water; bare ground. Also areas that have suffered a fire a short time earlier can be considered as barriers (Pyne et al., 1996).

2.2. Meteorological Conditions

The weather constitutes, if combined with some physiological conditions of fuel, the factor which mainly influences the fire behaviour. Dryness, strongly related to the fuel flammability and combustibility (Viegas et al., 1991), and wind play a key role during the flame front propagation (Rothermel, 1972). In many cases, meteorological conditions overcome the other elements of the fire environment triangle, so much to determine, alone, the behaviour and the dangerousness of a fire (Pyne et al., 1996). In the Mediterranean zones, the fire season is always associated with the period between late spring and the beginning of autumn; in this period the temperatures are more elevated and the fuel dryness is maximum. Meteorological factors are variable, sometimes even unexpectedly, both in space and in time and, unlike vegetation, cannot be controlled or managed by men. On the other hand meteorological factors can be forecasted, and a good knowledge of the meteorological condition evolution can be fundamental for the operations of fire extinction and management.

In the description of the most important meteorological factors tied to the fire propagation, the classification proposed from Velez (2000) is particularly valid. The meteorological variables can be classified into two groups:

a) variables influencing the possibility of fire ignition, because they have an influence above all on the fuel moisture; therefore, these variables exercise a limited effect on the spread of the event, and mainly they strongly influence the possibility that a fire can ignite more or less easily;

b) variables affecting the rate of spread, because they influence the flow of oxygen necessary for the combustion and the heat transfer processes; therefore the predominant effect of these variables is on fire behaviour.

METEOROLOGICAL VARIABLES INFLUENCING FIRE IGNITION. *Solar radiation* represents the energetic source of all natural processes. Its effect on fires is "indirect", since radiation affects various factors tightly linked with the fire behaviour (fuel moisture and temperature, day duration, etc.).

Precipitations can quickly modify the humidity of soil and vegetation, both live and dead. The effect of precipitations on dead fuel moisture is almost immediate, while for live fuel the moisture content changes after some days.

Air temperature has a direct influence on the energy needed to reach the ignition temperature and on the facility by which combustion happens. Air temperature has a fundamental effect on vegetation, both for dryness and for temperature of tissues. In the Mediterranean Basin, the effect of the temperature must be "adjusted" considering also the water availability (Kramer et al., 2000). In the vegetation heated by sun, ignition and combustion happen with greater velocity, and the spread rate is more elevated. In Mediterranean zones, air temperature presents a cyclical course, both daily and yearly. During the day the temperatures are more elevated in early afternoon; so also the fuel temperature reaches its maximum value in these hours. It is for this reason that fires reach maximum intensity values during first afternoon. During the year, the temperature peaks are recorded in summer, when the day duration and the angle of incidence of solar rays, regarding the land surface, are maximum.

Relative humidity, also because of its link with temperatures, in normal conditions presents a meaningful daily variation, with a minimum in central and warmer hours of the day and a maximum during the night. In general terms, relative humidity values inferior to 30% are favourable to fire ignition and propagation. The effects that the relative humidity exercises on fires can be referred to two elements. The first effect, even if not so important, is on the oxygen availability for combustion, since as relative humidity grows, atmospheric oxygen descends. The second effect is linked with the connection between relative humidity and fuel moisture. Dead and live fuels are physical elements exchanging humidity with atmosphere. This rate of exchange is inversely proportional to the dimensions of the fuel particles: small particles are more rapid to achieve an equilibrium with the humidity of surrounding atmosphere. The greater fuel moisture is, the greater energetic contribution to supply, in order to eliminate water from tissues and to carry the fuel to ignition temperature.

Lightnings represent, in some areas (i.e. mountainous zones of the United States), the main causes of fire ignition. Fires caused by lightnings can quickly assume important proportions: in fact thunderstorms are often associated with strong winds and incoming nightfall, so the fire extinction operations by direct and aerial attacks are hindered.

METEOROLOGICAL VARIABLES INFLUENCING FIRE RATE OF SPREAD. *Wind* represents the movement of air masses relative to the earth's surface and, like a vector, it is defined by its intensity and its direction. The wind direction is tied to differences in atmospheric pressure between two zones, since air masses move from high pressure towards low pressure zones. Because of the terrestrial rotation, the movement of air masses among zones with different atmospheric pressure does never follow a straight line, but tends to rotate. The force by which air masses move depends on the distance between high and low pressure and on the pressure gradient. At terrestrial surface level, local topographical characteristics can remarkably influence the anemometry, modifying wind direction and intensity. The more important examples of local winds, for which the general rule of air masses movement is not "respected", are sea and earth breezes and streams moving along a steep side. Among the meteorological factors affecting the fire behaviour, the wind represents the most variable and important. Variations of wind speed and direction take place during all the day, with a greater variability during afternoon, when the atmospheric conditions are more unstable.

During a fire, an air mass, named convective column, is produced; it tends to go up and its movement is regulated by the heat released from fire and by the thermal differences (in altitude) existing in loco: this is very important, because the events of big dimensions are able to originate their own meteorological conditions, and therefore they can "regulate" wind direction and intensity independently of the surrounding environment.

The effects that wind can exercise on fire behaviour are various:

- increase of the vegetation dryness, because of the increment of plant evapo-transpiration and the decrease of atmospheric relative humidity;
- increment of the oxygen flux and acceleration of the combustion process;
- greater inclination of flames, with consequent better transmission of energy towards unburned fuels and in slopes;
- greater possibility of ignition of spot fires, because of the ability to push up the particles in combustion towards the top of the convective column.

Wind is a fundamental element for fire behaviour, since it regulates its rate of spread and intensity, it can allow flames to cross defensive barriers and it can facilitate the transition to crown fires.

Atmospheric stability represents the resistance offered by atmosphere to the vertical movement of air masses. An unstable atmosphere favours the fire propagation, since it favours the motion of the combustion gases and the arrival of air masses from flanks, allowing fire to have a greater rate of spread: in these conditions, a fire can be very dangerous. On the contrary, when the temperature difference between air mass near the ground and air mass in altitude is limited, the air masses tend to return to their departure positions: when the atmosphere has such a degree of stability, wildfires difficultly have a frightening behaviour. Generally, the conditions of maximum stability are recorded during the night, while phenomena of instability are recorded in the central hours of the day.

2.3. Fuel (Vegetation)

The vegetation is the fuel on which the fire propagates and determines in a meaningful way the fire characteristics, because the fuel influences the easiness of ignition, the fire intensity and spread rate, and the height of flames (Pyne et al., 1996). The vegetation is the most studied among all the elements involved in the fire propagation, and its knowledge represents a key element for the understanding of the fire behaviour. It is also true that vegetation is typically very heterogeneous and discontinuous, and this aspect makes it difficult to characterize. Among the environmental factors, vegetation represents the only element that management practices can directly modify or control (Finney, 2001; Pollet and Omi, 2002).

2.3.1. Fuel Properties

The ***intrinsic properties*** of fuels are defined by chemical characteristics, density, thermal conductivity and heat content.

The chemical composition of a plant is the most important for its effects on the combustion process and the fire propagation. Vegetation is mainly constituted by water and polymeric organic and inorganic compounds:

- water, which brakes the combustion;
- cellulose and hemicellulose, main organic components of plants, are readily pyrolyzed;
- lignin is transformed in char, and only limited amount can volatilize;
- extractives (aromatic and aliphatic hydrocarbons, alcohols, aldehydes, sugars, gums, terpenes, waxes, oils), present in limited amounts, remarkably influence fire propagation and represent a large source of volatile combustibles, because of their volatility, high heat of combustion and low limit of flammability;
- minerals (or ashes) have a suppression effect on fire.

The chemical composition of the woody cells is approximately, in dry weight, 41-53% cellulose, 15-25% hemicellulose, 16-33% lignin, and the remaining part is constituted by extractives and ashes (Pyne et al., 1996). The percentage of lignin increases, with respect to the other components, in decaying plants and tissues. The herbaceous vegetation has a greater content in extractives and a lower content in cellulose and lignin with respect to woody fuels.

The fuel heat content represents the heat released from a unitary fuel amount (completely oxidized). Usually each species has a characteristic heat content (ranging from 18000 to 22000 KJ Kg^{-1}), but this value does not vary widely in forest fuels: the value of 18620 KJ Kg^{-1} is commonly used as standard.

The ***extrinsic properties*** of fuels are defined by fuel load, dimension and shape, compactness and arrangement.

QUANTITY OR LOAD. The fuel load represents the ovendry weight of fuels for a unitary area, and is often expressed in t ha^{-1}. The main advantage of expressing the vegetation load on dry weight basis, rather than in fresh weight, is to exclude the moisture content, generally variable, from fuels. Fuel load was also defined as measure of the potential heat that can be produced during a wildfire (Martin et al., 1989, Whelan, 1995, Pyne et al., 1996), since it represents the organic matter potentially involved in combustion. Such definition evidences that when the fuel load increases, also fire intensity and its dangerousness grow. Fuel load is variable, and is linked with the vegetation species: herbaceous plants are fuel type with lower load, while a greater fuel load can be found in logging slash areas (ranging from 70 to 450 t ha^{-1}) (Pyne et al., 1996). The ground fuel load is often considered separately, and it is specified in terms of "duff" depth; duff is the organic soil layer composed of humus, decaying leaves, roots, and other organic matter in decomposition.

SIZE AND SHAPE. Size and compactness of fuel particles regulate two important processes for the fire propagation: the heat transfer and the availability of oxygen for the fuel (Clar and Chatten, 1966). The fuel of smaller size has a better aptitude of ignition and facilitates the combustive process (Pyne et al., 1996). The energy necessary to remove water and to bring fine fuels to ignition temperature is inferior with respect to bulkier fuels. Fine fuels are essential to facilitate the fire front propagation. Moreover, with high presence of thin fuels, the ignition of new fronts with spot fires is more frequent. The size of the fuel particles is commonly defined by SAV, which indicates the ratio between surface area and volume of a particle, and it is expressed in cm^{-1} ($cm^2\ cm^{-3}$). The smaller SAV ratio is, the more voluminous fuel particles are. SAV ratio is an important element to define the fuel characteristics, because it is correlated to the rates of change in fuel temperature and in moisture content. A close relationship between SAV and some fire behaviour parameters also exists.

COMPACTNESS. The compactness represents the free spacing between fuel particles, and it defines the closeness of particles in the fuelbed. The compactness degree is tied to fuel load and depth, as well to particle dimensions. The packing ratio defines the fuelbed compactness, in terms of effective volume occupied by fuel. The bulk density is used in order to estimate the weight per unit volume of the fuel complex; the bulk density approximates the fuel porosity. When the fuel is compact, it is common to observe a slower fire spread rates (Biswell, 1989). Fuels with a smaller compactness react faster to moisture changes and have more oxygen for the combustive process.

ARRANGEMENT. The arrangement includes the orientation of the fuel particles (horizontal or vertical) with respect to the ground, and the spatial relationship between particles (Pyne et al., 1996). Shrubs and grass are vertically oriented fuel types, while timber litter and logging debris are horizontally oriented. Fuel horizontal orientation influences fire behaviour and can represent a determining element for flame propagation. A typical example is constituted by the continuity of canopies for crown fires. Orientation on a vertical plan influences the vegetation interested by fire: the vertical structure of the fuel can support crown fires or only ground or surface fires.

2.3.2. Forest Fuel Layers

The vegetation is typically classified by considering the position of its elements with respect to a vertical plan (Pyne et al., 1996); besides, the vegetation is also divided in dead or live fuels (Clar and Chatten, 1966). Forest fuels are compounds of different particle sizes of live and dead vegetal matter, arranged in complexes with different components, named layers. Sandberg et al. (2001) proposed an interesting classification scheme for the vegetation. This classification subdivides the fuel in six horizontal fuelbed layers: tree canopy; shrubs and small trees; low vegetation; woody fuels; litter fuels; ground fuels. These layers constitute the fuel on which fire propagates. Each fuelbed layer is subdivided in one or more fuel categories in its turn, considering physiognomical characteristics (morphological, chemical and physical characteristics), fuel availability and combustion characteristics.

To simplify, in my work the most common distinction for the fuelbed is described. Fuels are divided into (Figure 3):

- ground fuels;

- surface fuels;
- crown or aerial fuels.

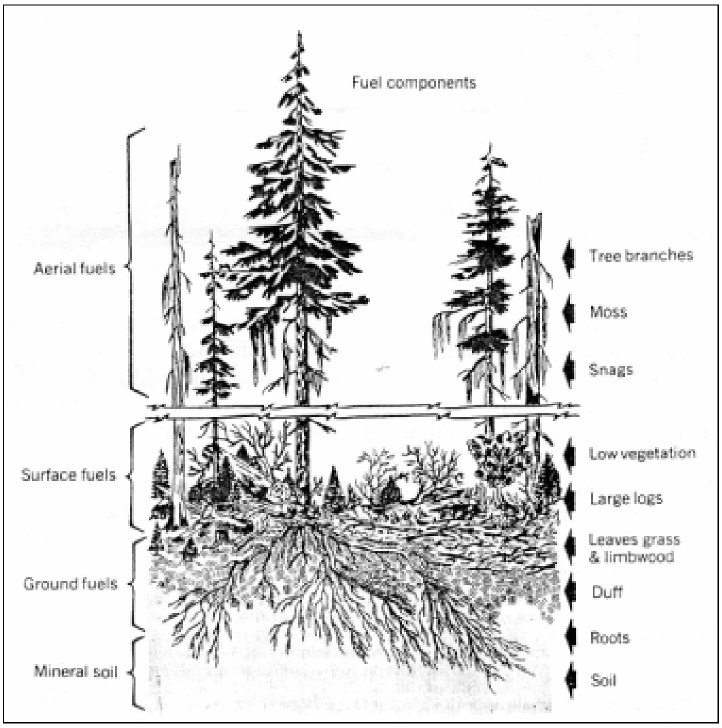

Figure 3. Fuel components categorized according to ground, surface, crown fuels (from Barrows, 1951)

GROUND FUELS. In this category roots, humus and material in decomposition on the ground (from the tiniest to tree logs) are included (Pyne et al., 1996; Sandberg et al., 2001). The ground layer in which humus and material in decomposition lie is named "duff". In the top of the duff, needles, leaves and other castoff vegetation material in the first phases of decomposition are present; these elements are typically bounded by fungal mycelium. The bottom of the duff is represented by mineral soil. The ground fuels are generally compact.

SURFACE FUELS. Surface fuels represent the more studied fuelbed layer, since most fires originate and propagate on this component (Pyne et al., 1996). Small trees, with maximum height of 2-3 m, shrubs, herbaceous vegetation, litter, woody residues of slash, are included in surface fuels. The surface component of the vegetation is generally not compact. The fire behaviour is different according to the characteristics of the surface fuelbed, depending on whether we consider the fire propagation only in litter, in grassland or in areas with shrubs and trees.

CROWN (OR AERIAL) FUELS. In this category tree crowns and shrubs with height over 2 m are included (Pyne et al., 1996). Except some particular cases, the aerial vegetation is largely constituted by biomass, with high moisture content: therefore the crown tree burns only if the heat released by the fire is maintained for long time or if the flames burn directly the crowns. So that the flames may arrive at the canopy, the presence of a layer of shrubs and small trees is necessary, in order to eliminate the gap between surface and aerial layer. The layer of small trees and shrubs, in this case, is defined ladder fuel. It is important to estimate aerial vegetation, because a crown fire cannot develop without it (Van Wagner, 1977).

2.3.3. Fuel Moisture

The amount of fuel available for the combustion process is linked with the amount of water in the vegetation (fuel moisture) (Pyne et al., 1996). In order to ignite a fuel, it is necessary to induce the water evaporation from tissues. The heat that must be supplied to remove water from vegetation is proportional to the moisture content. The fuel moisture is the result of the cumulative effects of past and present weather conditions; to this amount, the effect exercised by biological processes on biomass must be added. The fuel moisture varies in space and in time, sometimes also rapidly and within a single fuel element: this effect influences unavoidably the fuel flammability (Biswell, 1989). The fuel moisture content (*FMC*) is expressed in percentage, using as reference the dry weight, and it is calculated as:

$$FMC = \frac{M_{wet} - M_{dry}}{M_{dry}} \qquad (2)$$

The FMC is defined by per cent ratio between the water weight of the fuel sample and the weight of the same material dried up in stove; the water weight can be obtained by difference between the beginning weight of the fuel (M_{wet}) and its dry weight (M_{dry}).

DEAD FUEL MOISTURE. The amount of water in the fuel particles change continuously, depending on the humidity of the environment. The gain in moisture of the dead fuel is related to the action of liquid water and water vapour; the fuel drying is instead tied to evaporation (Pyne et al., 1996). Dead fuel moisture is influenced by all three legs of the fire environment triangle: weather, fuel and topography. As for the effect of vegetation, the most important elements are fuel composition (needles, leaves, duff, etc.) and size, as well as location; also the presence of some superficial layers, i.e. cortex or waxes, affects the dead fuel moisture. The location of the dead fuel is another important factor: ground dead fuel has a higher average moisture content and a more limited water content variability with respect to dead fuel laying in surface. Precipitations, wind, solar radiation, temperature and atmospheric humidity influence the dead fuel moisture. Solar radiation, in general terms, represents the meteorological factor that mostly affects the dead fuel moisture, influencing its temperature; its effect varies on hour, day, month, slope, aspect, latitude. Wind can have both a drying and a wetting effect.

A feature used to express the dead fuel moisture is the equilibrium moisture content (*EMC*), which defines the moisture content value if the fuel is exposed, for an infinite length of time, to constant atmospheric conditions of humidity and temperature (Pyne et al., 1996). In nature it is very rare to have constant atmospheric conditions, so EMC is useful to confront measures obtained on different fuels.

Dead fuel is classified according to the time fuel takes to reach the equilibrium with humidity variations in atmosphere. Timelag, or response time, is defined as the time required for dead fuel to lose about 63%[*] of the difference between its initial moisture content and EMC, in constant conditions of humidity and temperature. Timelag is generally expressed in hours. Each fuel is characterized for having a defined timelag. The average timelag interval varies especially in relation with the dead fuel size. Fuels are grouped, by considering their timelags, into four categories: lower than 2 hr, from 2 to 20 hr, from 20 to 200 hr, greater than 200 hr. An equivalent dead fuel diameter class corresponds to these four categories of average timelag (Table 1).

Table 1. Dead fuel timelag and diameter class

Dead Fuel Timelags	*Dead Fuel Diameter Class*
1 hr (0-2 hr)	0-0.25 inches - 0-0.6 cm
10 hr (2-20 hr)	2.5-1 inches - 0.6-2.5 cm
100 hr (20-200 hr)	1-3 inches - 2.5-7.6 cm
1000 hr (> 200 hr)	> 3 inches - > 7.6 cm

[*] this value is obtained by the calculation: $\left(1-\frac{1}{e}\right)$, where *e* is Nepero's number (a constant value approximately equal to 2,718).

LIVE FUEL MOISTURE. The influence that live fuel exercises on fire can be positive, since biomass supplies an additional source of energy during combustion, or negative, because it is necessary to supply more energy for the fuel ignition and for the water evaporation, and this can retard the fire propagation and intensity. Unlike the dead fuel moisture, linked with meteorological conditions, the biomass presents seasonal variations in moisture connected with physiological and phenological processes of plants. The moisture content of leaves in many fuel types varies remarkably during the year, and it is regulated above all by the weather conditions and the pheno-physiological characteristics of plants. In herbs, the minimum moisture content coincides with the plant death. In shrubs and in deciduous tree species the minimum level of leaf moisture is recorded before leaves fall. In shrub and evergreen species, because of the continuous presence of leaves, the minimum leaf moisture value is higher than the value of other plants. The fluctuation of the leaf moisture content is characterized by a series of irregularities: such an irregular trend is common for the herbaceous species, which are very sensible to short period and seasonal meteorological conditions.

2.3.4. Fuel Classification

The variability of the vegetation requires the use of classification systems that supply accurate descriptions for the different fuelbed types. In the last years, various classification systems have been proposed. The most important are presented below.

The *fuel classification system by direct estimation* recurs to a subjective opinion executed by a specialist who has matured experiences with wildfires on similar parcels (Chandler et al., 1983). This procedure has been created by U.S. Forest Service around 1930 (Hornby, 1936). The fuel was rated into categories, based on the fire spread rate and on the resistance to control, in "normal" meteorological conditions. The main problem of this system is not the subjectivity, but that the fire behaviour for a defined vegetation type in normal meteorological conditions can be completely different from severe or low risk conditions. This method has been the official fuel classification system in USA until about 1970.

The *fuel classification system by plant communities* uses specific silvicultural and ecological nomenclature and fire behaviour definition for each category by considering historical data and expert opinions (Chandler et al., 1983). This system has the advantage of being flexible and understandable. A valid method has been proposed by Trabaud (1974, 1978) for Southern France, and it consisted in considering both floristic and physical features of plant communities. The first step was the calculation of the relative proportion of trees, shrubs and herbs; therefore the volume occupied by each class was estimated to characterize phytomass; at last, since some stands may be physically similar but can have different combustion characteristics, they were typed by 2-3 dominant species. One of the disadvantages of this classification system is that the production of a vegetation map may be very subjective, so an area can be typed using different classification schemes according to authors; moreover, if the classification system is narrow, the fire behaviour information results expensive and time-consuming (Arno and Sneck, 1977).

Some *fuel classification systems by dichotomous keys* have been developed. They were based on blowup potential (Wendel et al., 1962), on rate of spread, or on crowning potential (Fahnestock, 1970; Chandler et al., 1979). This classification system has some points of strength, which are, at the same time, also weakness elements. In fact the choices are subjective, and only experts can be able to correctly classify the vegetation using dichotomous keys.

The *fuel classification system by fuel models* is very important. A fuel model is a mathematical representation of the surface fuels, with all the variables necessary to calculate the main characteristics of the fire behaviour, in particular the spread rate and the fireline intensity (Deeming, 1975). Therefore, a fuel model can be defined as a complete set of fuel inputs for mathematical fire spread model (Rothermel, 1972). A fuel model represents all vegetation types whose characteristics (load, SAV ratio, etc.) are equivalent to those of the same fuel model. Since a fuel model is not based on floristic parameters, but on physical parameters of the fuelbed, a single fuel model can represent a wide variety of fuel types (Chandler, 1983). Moreover, unlike other fuel classification systems, the fire behaviour characteristics can be easily computed over the full range of meteorological and topographical conditions. To these advantages, some negative elements can be opposed: the validation of the fuel models is difficult and expensive (Bevins and Martin, 1978), and moreover a purely mathematical representation does not "illustrate" perfectly the fuel types present on landscape.

The *fuel classification system by photographic guides* combines the approaches based on the use of plant communities and fuel models (Chandler et al., 1983). With this system, small plots are selected as representative of defined fuel types; after some adequate photographs on the studied vegetation, the fuel characteristics are described. Subsequently, the plots are dissected in sections and all fuelbed characteristics, necessary to define the fuel model, are measured. At present, the most used classification system in the world is the one based on photographic guides summarized by fuel models: various examples of vegetation classification obtained with this system are available in literature (Albini, 1976; Deeming et al., 1977; Anderson, 1982; Cruz, 2005; Scott and Burgan, 2005; etc.). The main problem of the classification system by photographic guides is tied to high costs (Chandler et al., 1983), since the work of many persons at the same time is necessary; it must be added that this methodology is complex and time-consuming.

In the last years, the definition of the different fuelbed classes is mainly obtained with information derived by ground sampling, remote sensing and aerial photography imagery, and ecological gradients analysis.

3. Fire Growth Phases

During a fire it is possible to distinguish some potential phases of growth or evolution: these phases take place in chronological order. Emmons (1966) created a classification of the fire growth phases, proposing the distinction of six main potential phases during a spreading fire: ignition, build-up, stationary equilibrium, decay, flame extinction and cooling of residues until they reach ambient temperature. More recently, André (1996) suggested the distinction of eight potential development phases:

1) **Ignition**. It is the beginning phase of each fire and brings forest fuel to a condition of "self-supported" propagation of the flame front.

2) **Build-up**. The fire reaches the propagation regime named stationary or semi-stationary. The fire spread acceleration is positive, but it tends to decrease asymptotically in time until it becomes null.

3) **Full Development of Fire Regime**. The fire is fully developed and it assumes a stationary or nearly-stationary behaviour, mainly determined by environmental conditions and by fuels. The phase of full development interests the most of the fire duration. In this phase all the possible fire behaviours can be present, so the studies are concentrated in particular on this third phase.

4) **Possible Transition to a New Spread Regime**. Some fires can present a fourth development phase, during which a transition of the spread regime can be possible: the transition is induced by meaningful changes of vegetation, topography, and/or meteorological conditions. This phase is generally very fast, because of the strong and not linear effects that are involved. Among the most important regime transitions, the passage from moderate surface fires to "blow-up", which takes place during big fires burning trees or shrubs, can be mentioned.

5) **Decay**. The fire reaches an unstable phase of decay when environmental conditions change (increment of fuel moisture, onset of opposite winds, etc.), reducing the spread of fire. Although in this phase the fire has a not stationary behaviour, for short intervals a nearly-stationary spread regime can be recorded: this regime belongs to a specific class of fires, named marginal fires (André et al., 1992).

6) **Flame Extinction**. The previous phase of decay is followed by the flame extinction, for flaming fires.

7) **Smoldering Combustion**. The phase of smoldering combustion occurs immediately after the sixth phase, and protracts until the extinction of the smoldering combustion regime. The smoldering combustion is characterized by:

- combustion of the fuelbed particle surface, reduced to coal;
- very limited oxygen demand;
- fuel consumption rate very low and, therefore, high residence time (Chandler et al., 1983).

8) **Cooling of Combustion Residues**. In this last phase, the combustion residues cool until they reach ambient temperature.

Therefore, like organisms, the wildfires have an origin and a growth phase; they can reach "maturity", decay and finally die (Viegas, 2005a) (Figure 4). These potential fire phases can be observed, during a wildfire, at different time or in different sites at the same time.

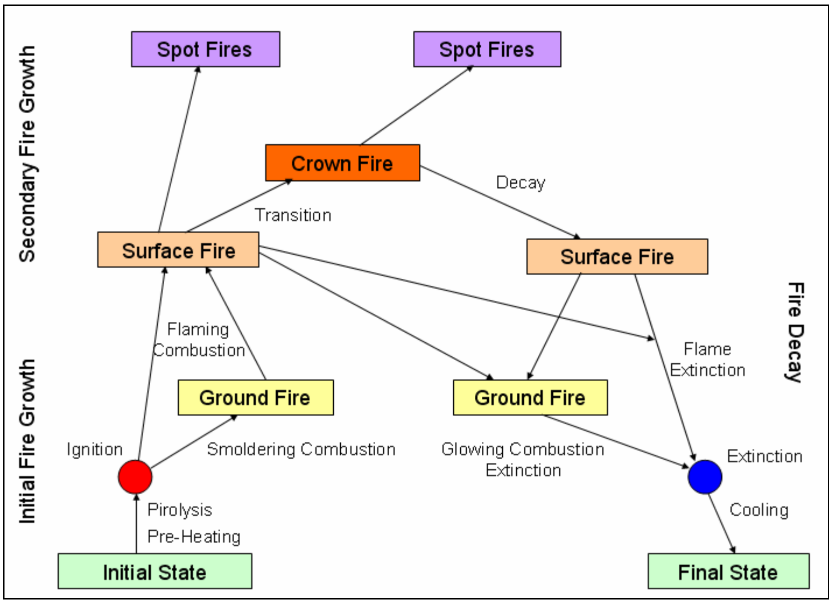

Figure 4. The fire evolution: ignition, growth and extinction (adapted from Viegas, 2005a)

4. Fire Propagation Regimes

The fire propagation regime refers to a defined typology of stationary or nearly-stationary wildfire behaviour. Observations of real fires and laboratory and field experiences have demonstrated that various regimes of fire propagation exist, and that among these regimes remarkable qualitative differences can be found. However, for short periods, during a fire, some not stationary phases are also recorded, for example during build-up or decay phases. Four criteria of classification of the fire regimes exist, based on (André et al., 2006):

a) the combustion regime in the fire front (Kanury, 1976): it can be distinguished into regimes without flames, with glowing or smoldering combustion, or regimes with flames, with flaming combustion;

b) the type of forest fuels in which the fire front spreads: this classification divides fires into ground, surface and crown fires (which are either free or dependent on surface fires) (Brown and Davis, 1973);

c) the sensitivity of the fire response to a change in a given input parameter of fuelbed or environment;

d) the order of magnitude of values of some properties of the fire front, such as rate of spread (slow and fast fire regimes) or fireline intensity (low, medium and high intensity fire regimes).

Among these four classes of fire regimes, certainly the most known classification criterion is the second one.

4.1. Surface Fires

Surface fires interest litter, trees of small dimensions, shrubs and herbaceous biomass, and dead fuel accumulated on the ground surface (DeBano et al., 1998). During its propagation, a surface fire can provoke the ignition of dead trees lying on ground, can destroy vegetation, and can cause “torch out” of big trees with dense foliage and vertical continuity between terrain surface and canopy. A fire is named surface fire until its rate of spread depends only on surface fuel: when other mechanisms take place, as for example spotting or crown fires, the fire propagation regime cannot be defined as surface regime, even if it interests also that specific vegetation. Being the most diffuse regime, as well as the most important in Mediterranean areas, numerous studies are focused on this topic. All the following treatment of the fire models will make reference to surface fires; so a detailed treatment of this fire type will be presented later on.

4.2. Ground Fires

Ground fires are typical in zones where a deep organic soil layer is present, in areas with accumulations of organic matter, in its several states of decomposition. These fires interest all the organic matter in the organic layer, so the most affected elements are duff and roots. Since the ground fuels are compact, the ground fires propagate with a very low spread rate, and in most cases the combustion is without flames. The ground fires are persistent, difficult to control and expensive to extinguish, both in economic and time terms. The ground fires, perhaps because of their limited intensity (the combustion regime without flame is less energetic than surface or crown fires), are not object of many researches, even if they have some characteristics (André et al., 1992):

- they are probably the most toxic, because of the incomplete character of pyrolysis reactions and of glowing combustion (Kanury, 1976);
- they are difficult to detect;
- they are the most harmful for the organic soils (loss of organic matter, erosion, soil element volatilization) (Hungerford et al., 1991).

4.3. Crown Fires

The spatial continuity and the canopy density, together with the environmental conditions (in particular wind), supplies the necessary conditions to the propagation of intense fires able to burn the tree crowns in wooded zones (Graham et al., 2004). A surface fire can become a crown fire in relation with the surface fire intensity and with some crown characteristics (Van Wagner, 1977; 1993). Crown base height, crown bulk density and crown continuity are typical elements of a forest structure that influence the crown fire ignition and propagation (Albini, 1976; Rothermel, 1991) (Figure 5).

The *crown base height*, the height to which crown begins, is important because it influences the transition to crown fires. With limited crown base height, the crown fire ignition, from a surface fire, is easier. The *crown continuity* is hard to quantify.

Low uniformity reduces fire propagation inside tree crowns. The *crown bulk density* represents the crown weight for a defined volume, and varies considerably inside a forest.

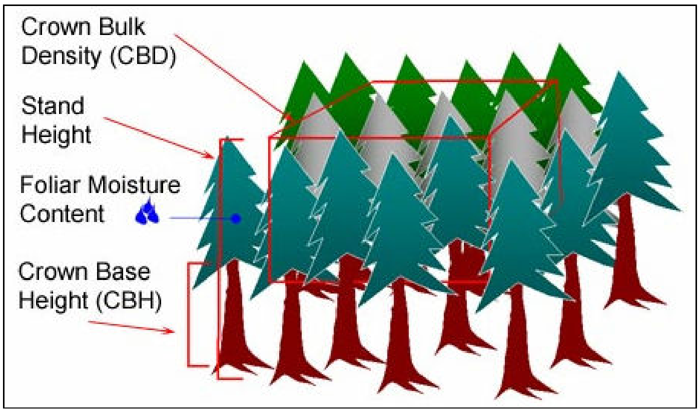

Figure 5. The main crown parameters influencing crown fire (from Finney, 2007)

Two categories of crown fires can be distinguished: *active* or *passive* (Van Wagner, 1977). To these categories a third one can be added: *independent* crown fires (Finney, 1998) (Figure 6).

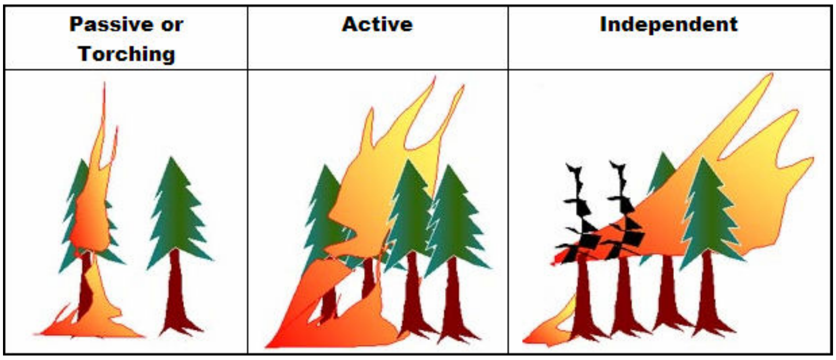

Figure 6. The three crown fires typologies (from Finney, 2007)

In order to distinguish the first two crown fires typologies, a comparison between the actual crown fire spread rate and the critical rate for transition to an active crown fire is necessary: if the value of crown fire spread rate exceeds or not the threshold value, fires are respectively distinguished into active or passive. The independent crown fires are so defined because they are not dependent on surface fires, unlike other two types; in these circumstances the crown fire precedes the arrival of the surface fire. There is an important difference between active and passive crown fires. For the first, the rate of spread remains equal to the surface fire rate of spread, but the intensity of the fire front and the flame length increases; for passive crown fires, the rate of spread is higher with respect to the surface fires, as also the intensity of the fire front and the length of flames.

Another classification distinguishes crown fires into wind-driven fires and plume-dominated fires (Rothermel, 1991). If the wind intensity is higher than the energy of the fire convective column, a *wind-driven crown fire* will develop (Figure 7). The wind speed profile will show an increment of intensity with height: therefore, the wind will push the fire spread and it will orient the direction of the convective column according to the wind direction (Pyne et al., 1996). These crown fires are characterized by showers of sparks and embers, and by high probabilities of spotting fires ahead of the flaming front.

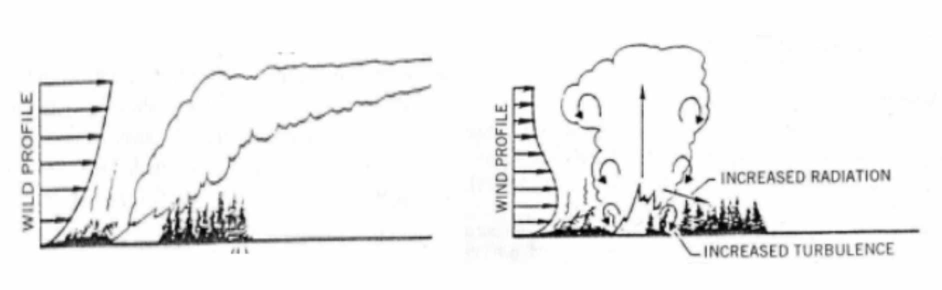

Figure 7. Wind-driven crown fire (left) and plume-dominated crown fire (right) (from Rothermel, 1991)

A fire in which a convective column develops vertically over the fire front is instead a *plume-dominated crown fire* (Figure 7 and Figure 8). Some researchers suppose that in these cases strong turbulent flows take place; these flows move towards the bottom and promote the combustion process. The increment of the fire turbulence and intensity increases, in their turn, the heat transfer by radiation and convection, with an acceleration of the spread rate. This process can explain why, in some fires, rates of spread unexpectedly elevated can be observed, regarding anemometric conditions (Pyne et al., 1996).

Figure 8. Hayman wildfire convective column (from Graham et al., 2004)

4.4. Extreme Fire Behaviour

Some fires are very dangerous because they can assume extreme behaviours, exceeding the "normal" characteristics recorded in most fires (Pyne et al., 1996). The extreme fire behaviour occurs on a small percentage of fires, but has major effects: it is estimated that 10% of the fires in southern California account for over 90% of the burned area (Minnich, 1998). Therefore, although few fires can manifest so dangerous behaviours, their study is important: a fire with these characteristics can provoke huge damages and problems for safety and for control and suppression interventions.

The *crown fires* have already been discussed in the previous pages. Such events develop with other peculiar phenomena, among which the most important are horizontal roll vortices, spotting and fire whirls.

The *horizontal roll vortex* is a very extreme event where rotating air moves horizontally, driven by strong winds. Really, the crown fires sometimes do not burn completely all the vegetation inside the burned perimeter: some cases in which unburned forest fuel was concentrated on elongated strips, called streets (Figure 9), have been signalled (Pyne et al., 1996).

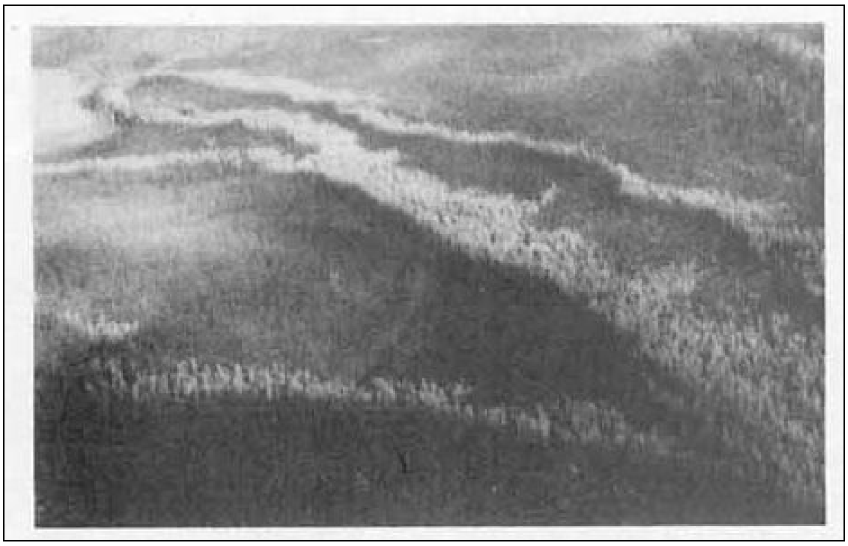

Figure 9. Tree crown streets resulting from Sioux Lookout Fire, USA, 1979 (from Haines, 1982)

This fact has suggested that during a crown fire warm air flows can develop, from the convective column towards the vegetation, provoked by horizontal roll vortices, which kept fire (and therefore flames) out of the crowns, creating such strips (Haines, 1982; Haines and Smith, 1987). The horizontal roll vortices move horizontally (this fact explains the horizontal strips), until the dissipation and the formation of other vortices, originated as result of the fire expansion.

A fire is named *spotting fire* when firebrands or pieces of burning materials are carried beyond the burning zone and provoke new ignitions in the landing points, originating spot fires (Clements, 1977; Albini, 1979; Pyne et al., 1996) (Figure 10 and Figure 11). Spotting is an important mechanism for the fire growth, with which in extreme conditions new flame fronts can start kilometres in front of the departure point of firebrands. The spot fire distance is primarily tied to wind speed and fire intensity (Morris, 1987), whereas the spot fire density mainly depends on the characteristics of the potential firebrand for a given fuel type (quantity, shape, size, particle density, etc.) (Alexander, 2000).

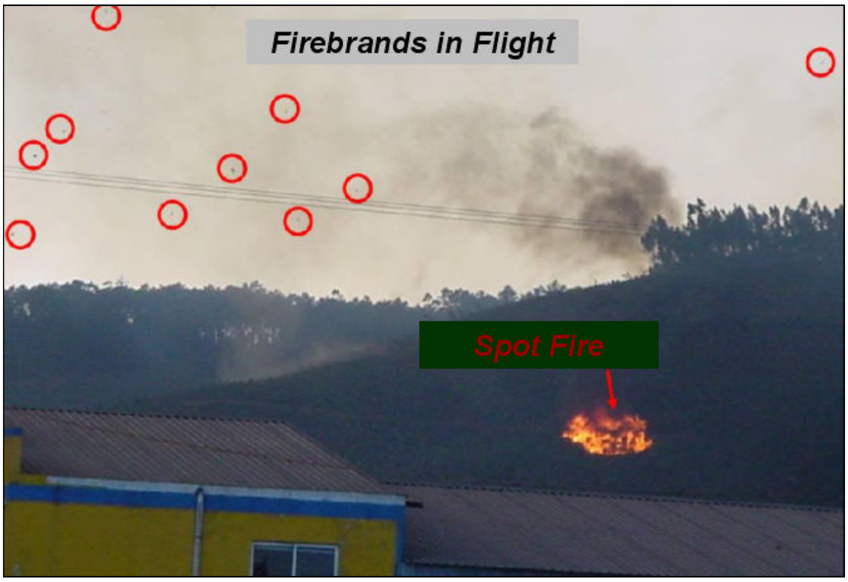

Figure 10. New fire front originated by firebrands in Cume, Portugal, 2002; the distance from the main fire front was approximately 850 m (Rossa, 2007)

As for spotting fires some features are fundamental (Pyne et al., 1996):

a) source of firebrands;

b) type, size and number of firebrands produced;

c) distance that firebrands are carried and means of transport;

d) ignition of spot fires.

The forest fuels able to originate burning firebrands are various: among the most important, pinecones, herbaceous plants tufts, pieces of bark, twigs, moss. To be effective, a firebrand must continue to burn during the flight transport and it must supply sufficient heat source when it lands. Small firebrands can cover great distances, but they often land already extinguished or with limited chance to originate spot fires; on the contrary, bigger firebrands usually travel shorter distances, but, when they land, they may stay ignited longer than smaller embers, and consequently new fire fronts can originate.

Although it is a phenomenon associated with crown fires, spotting is possible also with surface fires, in extreme environmental conditions. In general terms, the greater fire intensity is, the more important spotting (and consequently ignition of spot fires) is.

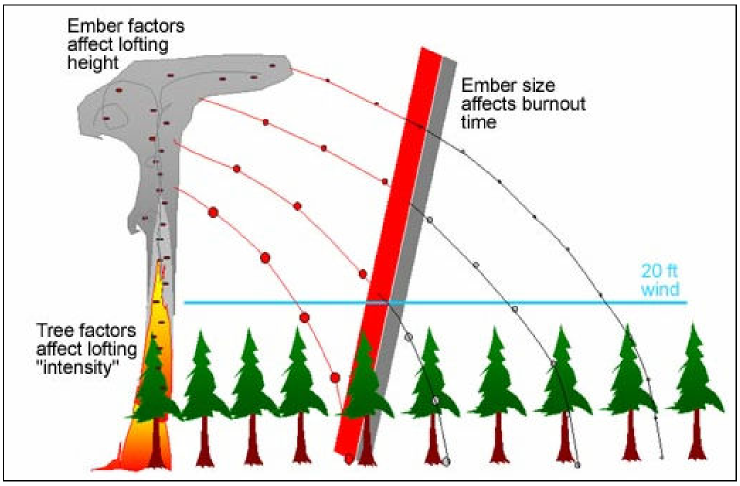

Figure 11. An illustrative scheme of spotting fires (from Finney, 2007)

A *fire whirl* is a vortex, a gas mass with rotational motion (Pyne et al., 1996). Fire whirls can greatly vary in size, strength and duration: most of them are small, but sometimes a fire whirl with destructive strength and size can develop. Usually the fire whirls develop near the ground, but occasionally they can develop above ground and then extend down, like a tornado. The formation of the fire whirls is linked with the rise in columns of the air heated by fire: some columns develop a strong rotational motion (Pyne et al., 1996). The fire whirl formation increases significantly the combustion rate, which in its turn increases the fire intensity and the fuel consumption. To these elements, the generation of high intensity winds, which allow the fire whirl to transport firebrands, must be added, increasing therefore the ignition of spot fires.

5. Main Characteristics of Fires

5.1. Shape and Parts of Fires

The shape assumed by wildland fires is strongly tied to the environmental conditions in which fires spread. The studies demonstrated that, for surface fires, there is a connection among propagation, wind direction and slope. It is also verified that a fire assumes more oblong shapes as wind intensity and slope become higher. In order to describe the shape assumed by fire, as a result of a single ignition point, the elliptical shape is often used (Pyne et al., 1996): the more the environmental conditions keep uniform, the more the shape tends to be elliptical.

In a surface fire it is possible to distinguish a series of "anatomical parts" that univocally characterize it (Alexander, 2000) (Figure 12).

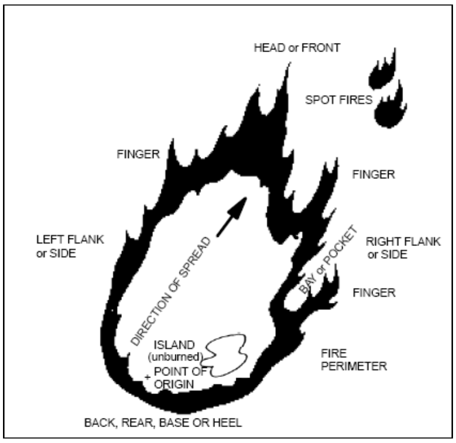

Figure 12. Anatomical parts of a fire (from Alexander, 2000)

In particular, three regions can be evidenced, in relation with the orientation of the edges with respect to the main wind direction and the rate of spread:

- heading fire;
- backing fire;
- flanking fire.

The *heading fire* represents the front zone of fire, and it is the zone with the most elevated propagation rate. The heading fire is the part that more directly moves towards vegetation not burned yet, under the effect of wind and, eventually, topography. In extreme conditions, above all when the wind intensity is very strong, the heading fire cannot operate combustion efficiently, releasing dense and black smoke and leaving a part of vegetation partially burned.

The *backing fire* represents the back area of fire, and it is the one with the most limited propagation rate. The flames, because of the effect of wind or slope, are inclined towards the vegetation already burned, and can provoke the ignition of the fuel backwards: therefore the backing fire propagates upwind and/or counterslope. It is for this reason that its propagation rate is so limited and operates independently of the main environmental factors. Unlike heading fire, combustion is often complete and efficient, and there is a smaller release of smoke and the production of small ash residuals, above all for some type of vegetation.

The *flanking fire* is represented by the lateral parts of fire: the flanks of flames are disposed parallel regarding the main wind direction. The flames are inclined along the fire flanks, and because of the changing direction of wind they can sometimes originate heading or backing fire. Therefore, the flanking fire assumes intermediate characteristics between backing and heading fire.

5.2. Main Elements of Fire Fronts

In a surface fire, some parameters are useful in order to obtain important information for the description of the fire front. The main elements used to describe a fire front are: flame height; flame length; flame angle; flame depth.

The *flame height* is the vertical distance that continuous flames extend above the fuelbed (http://www.ffp.csiro.au) (Figure 13); moreover it is used in the equations on crown fire transition (Van Wagner, 1977; Cruz et al., 2006). The measure of this feature is not simple, because of its variability: it is easy to record the height of flames in single observations, but it is difficult to define an average value. The flame height is generally evaluated observing the average maximum height of continuous flames in a unit of time (commonly a minute) and for a defined distance on fire perimeter (10-15 meters).

The *flame length* (Figure 13) is used to describe fire intensity and difficulties for the suppression operations (Alexander, 1982), and it is the distance from the base of the flaming zone to the top of continuous flames. It is a difficult feature to estimate in field, because of wind, fuels and fire behaviour changes, and because the observer may be standing at an angle to the fire front (parallax error).

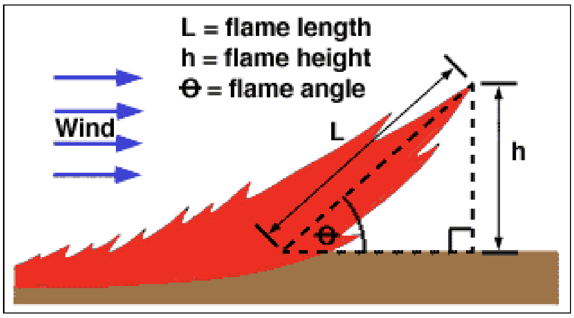

Figure 13. Length, height and angle of flames

The *flame angle* (Figure 13) represents the angle between the ground and the average flame around the flaming zone. This feature is strongly influenced by the wind on fire front and by the convective column.

The *flame depth* (Figure 14) constitutes the distance between the fire front and the backing fire zone, characterized by the presence of continuous flames. Therefore, the depth of flames is difficult to estimate for big fires. Such parameter is tied to the spread rate and to the residence time of flames*, and it is a useful indicator because it supplies the information about type and amount of burned fuel.

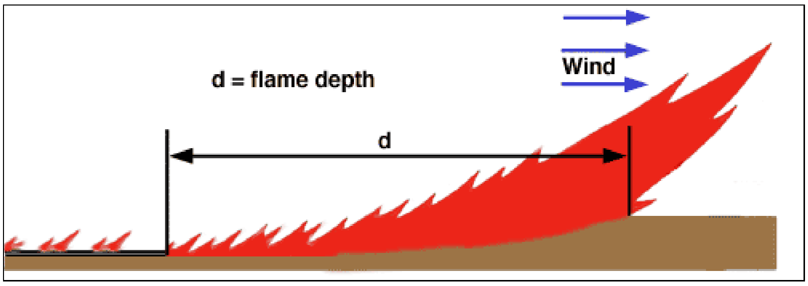

Figure 14. Flame depth

5.3. Fire Spread and Intensity

During a fire, some features allow to quantify intensity and easiness of fire spread (Pyne et al., 1996). The range of these fire characteristics is very wide,

* time of residence indicates the time during which the flames stay over a particular point in the fuelbed

considering that fire intensity and rate of spread can assume different values depending on cases.

The *rate of spread* (ROS) defines the rapidity of the fire propagation and measures the distance covered by the fire (from any particular point of the fire perimeter, in perpendicular direction to perimeter) during a defined time. Since the environmental conditions are in continuous evolution and change in time and in space, the spread rate represents the average value recorded in the unit time. The fire zone with the most elevated propagation rates is the heading fire, while the one with the most reduced values is the backing fire; the flanks of fire have intermediate ROS (Catchpole et al., 1992). The fire rate of spread is influenced in large measure by two elements: wind intensity and slope: if a fire moves in the same direction of wind and slope, the spread rate can reach elevate values. Also fuel influences the propagation rate, in particular, for surface fires, with the fine dead fuel (1 hr). Spread rate is measured in the heading part of a fire. It can vary from a minimum of 1.5 m h^{-1} (the inferior limit of spread for a fire burning surface fuels), to beyond 20 km h^{-1} in areas with grass fuel (Alexander, 2000).

The *fire intensity* defines the heat released by a fire per unit time (Pyne et al., 1996), and it is a valid measure to define the difficulty of containing a wildfire (Alexander, 2000). In order to calculate fire intensity, various modalities exist (Byram, 1959; Rothermel, 1972; Andrews et al., 2005).

The *reaction intensity* is much used. It defines the energy release rate, that is the energy produced per unit time from a unitary surface in the flaming zones, expressed in J min^{-1} m^{-2}*, or W m^{-2}. The *heat for unit area* represents instead the energy produced from a unitary surface in a period of time in which the flaming zone is on a defined area, and it is measured in W or J m^{-2}. Another useful parameter is the *fireline intensity*, which defines the energy released per unit time from a strip of unitary length extended from the heading part to the back of fire, and it is measured in W m^{-1}. The observed values of fireline intensity vary from 10 kW m^{-1} (the observed minimum value during flaming combustion) till values of 105 kW m^{-1}, during extreme fire behaviour (Alexander, 2000).

A detailed treatment of the equations defining fire spread and intensity is presented in the next chapters.

* (1 W = 1 J s^{-1})

FIRE BEHAVIOUR SIMULATION SYSTEMS

The fire behaviour simulation systems are software applications which are capable to supply information and data on both the simulated fire perimeter and the main parameters related to the fire spread and behaviour; in addition, a graphical or tabular visualization of fire parameters is usually provided.

A fire simulation system is constituted by two elements (Albright and Meisner, 1999): (1) a fire prediction model, which represents the core of the simulator, and simulates the fire propagation by considering the environmental conditions, and (2) a fire simulation technique, by means of which the parameters describing the fire spread and behaviour are compounded along the landscape.

In the last decades, a broad range of fire simulators was realized by researchers (Table 2), using different fire prediction models and simulation techniques. In relation to the fire prediction model, the semi-empirical and empirical approach is most appropriate for the incorporation into a wildland fire calculation system for operational intended uses, training or real time simulation purposes (Johnston et al., 2005). At present, the alternative approach based on physical models is limited to the description of chemical and physical processes during the fire combustion and spread.

By considering the various characteristics of the fire prediction models and the fire simulation techniques, it is possible to evidence the differences among the fire simulation systems, and also to estimate the similarities.

Most of the fire simulators are mathematical, and they are based on Rothermel's semi-empirical fire prediction model (1972) as incorporated into the BEHAVE Fire Behaviour Prediction and Fuel Modelling System (Andrews, 1986). Differences among simulators include the integration of procedures, the treatment of fire extinction and fire effects, and the incorporation of other methodologies for obtaining secondary fire behaviour parameters or meteorological variables (Pastor et al., 2003). The BEHAVE software was developed in the eighties by the United States Department of Agriculture and Forest Service, and it was based on Rothermel's studies (1972). This software permitted the evaluation of some fire behaviour parameters like the rate of spread or the fireline intensity of surface fires, by considering the environmental conditions. In the latest version of BEHAVE (Andrews et al., 2005), crown and spot fire modules have been implemented; in addition, the graphical interface has been improved. Other fire behaviour simulator systems have been developed in many other Countries (Australia, Canada, etc.) in the following years.

Table 2. The main fire behaviour simulation systems (from Pastor et al., 2003)*

NAME	COUNTRY	AUTHORS	MAIN CHARACTERISTICS	
BURN	United States	Veach et al. (1994)	SFM Rothermel	Cellular simulation technique (cellular automaton)
CARDIN	Spain	Martinez Millàn et al. (1991)	SFM Rothermel	Cellular simulation technique
DYNAFIRE	United States	Kalabokidis et al. (1991)	SFM Rothermel	Cellular simulation technique (cellular automaton)
EMBYR	United States	Hargrove et al. (2000)	SFM Hargrove et al.	SM Albini; Cellular simulation technique (bond percolation)
FARSITE	United States	Finney (1994)	SFM Rothermel CFIM Finney	SM Albini; Wave simulation technique; CFSM Scott and Reinhardt
FIREGIS	Portugal	Almeida et al. (1997)	SFM Rothermel	Cellular simulation technique (cellular automaton)
FIREMAP	United States	Ball and Guertin (1992)	SFM Rothermel	Cellular simulation technique (cellular automaton)
FIRESTATION	Portugal	Lopes et al. (1998)	SFM Rothermel	Cellular simulation technique
GEOFOGO	Portugal	Vasconcelos et al. (1998)	SFM Rothermel	Cellular simulation technique
INTEGRATED INFLAME SOFTWARE SYSTEM	European Union	Viegas (2000)	Viegas et al.; Marguerit and Guillaume	Cellular simulation technique
MEFISTO-AIOLOS-F	Greece	Lymberopoulos et al. (1996)	SFM Croba et al.	Cellular simulation technique
PFAS	Canada	Anderson (2002)	SFM Forestry Canada Fire Danger Group	CFSM Forestry Canada Fire Danger Group; Cellular simulation technique
PROMETHEUS	Canada	Canadian Wildland Fire Growth Model Project Team (1999)	SFM Forestry Canada Fire Danger Group	CFSM Forestry Canada Fire Danger Group; Wave simulation technique
PYROCART	New Zealand	Perry et al. (1999)	SFM Rothermel	Cellular simulation technique
SIIF TRAGSATEC	Spain	Alvarez (1996)	SFM Rothermel	Cellular simulation technique
SIROFIRE	Australia	Coleman and Sullivan (1995)	SFM McArthur	Wave simulation technique
SPARKS	Switzerland	Schöning (1996)	SFM Rothermel	Cellular simulation technique
SPREAD	Portugal	Mendes-Lopes et al. (2000)	SFM Rothermel	Cellular simulation technique (cellular automaton)
WILDFIRE	Canada	Wallace (1993)	SFM Forestry Canada Fire Danger Group	CFSM Forestry Canada Fire Danger Group
SFM = surface fire model; CFIM = crown fire ignition model; CFSM = crown fire spread model; SM = spotting model				

* Johnston et al. (2005) added to this list the fire behaviour system proposed by Vakalis et al. (2004a; 2004b).

6. Fire Prediction Models and Their Classifications

The fire prediction models are tools that are able to simulate the fire behaviour using site-specific data such as weather, terrain, and fuel type and conditions (Albright and Meisner, 1999). The fire prediction models are generally composed of a collection of equations, the solution of which gives numerical values for spatial/temporal evolution of the different fire variables, such as rate of spread, flame height, ignition risk or fuel consumption (Pastor et al., 2003). Various classification systems of fire prediction models exist (Perry, 1998; Albright and Meisner, 1999; Pastor et al., 2003; Johnston et al., 2005), according to the nature of equations for the energetic flow modelling, the types of studied variables or the modelled physical system.

6.1. Classification based on the Heat Flow Modelling

Many important equations of mathematical models attempt to model the flow of energy produced during the fire combustion (Albini, 1985). Actually the process of fire spread consists in the release of energy due to combustion and the transport of part of this energy to the adjacent unburned fuels, which are subsequently heated to ignition temperatures (Albini, 1985). The reconstruction of the energetic flows allows to define the most probable space-time evolution and propagation of fires. The different predictive methods used to quantify these processes differentiate, quantitatively and qualitatively, the various types of fire prediction models (Albright and Meisner, 1998). The classification of these predictive models has been organized in different ways, according to authors. In the next pages, the classification scheme proposed by Albright and Meisner (1998) has been used; these authors have distinguished four types of fire predictive models.

In *physical* (*or theoretical*) *models* the fire propagation prediction is based on the mathematical analysis of the physical-chemical laws that govern fluid mechanics, combustion and heat transfer (radiation, convection, conduction). Analysis or correlations with observed or laboratory fire experiments are instead not considered (Perry, 1998; Albright and Meisner, 1999; Pastor et al., 2003; Johnston et al., 2005). Therefore the results obtained must be subsequently validated and calibrated by tests (Catchpole and De Mestre, 1986). Theoretical models assume the knowledge of all parameters of the chemical processes, and they use a series of variables as input, among which, for example, flame temperature and height: therefore, physical models contain some degree of empiricism, considering that some inputs (i.e. flame height and stack gas viscosity) are very difficult to measure in field (Chandler et al., 1983; Beer, 1991) and, secondly, the processes of heat transfer are neither temporally nor spatially constant (Perry, 1998). The greatest advantage of theoretical models is that they are based on well-known relations, so it is easy to make comparisons (Chandler et al., 1983). Although various physical models have been developed, few of them are used, for several reasons (Perry, 1998; Albright and Meisner, 1999). First of all, they need a remarkable amount of information and data, and, considering the complexity of equations, the use of vast computing resources to solve them is necessary (Albright and Meisner, 1999; Johnston et al., 2005). Moreover, because of the complexity of equations and forest fuel structure, several semplificative assumptions are required (i.e. fuel characteristic uniformity); these simplifications are not always fit to reality (Johnston et al., 2005). Therefore, the validation of a theoretical model is particularly difficult.

Semi-physical (*or semi-empirical*) *models* are a "combination" of theoretical and statistical models, since they both adopt physical and statistical techniques. Such models combine the physical theory about combustion and the heat transfer with statistical correlations based on observations on laboratory fire-experiments, with the aim to define mathematical formulas able to describe the fire behaviour (Albright and Meisner, 1999; Pastor et al., 2003). In semi-empirical models, the burning fuel is treated as a source of heat while heating and evaporation of fuel and moisture are sinks for heat. Laboratory and field experiments are conducted to determine how physical properties of fuel, weather and slope contribute to each of these variables (Johnston et al., 2005). The employment of such models in environmental conditions not similar to those tested in laboratory or field (i.e. very strong winds, elevated temperatures) may not be very accurate, so validation is however necessary; difficulty in validation of semi-physical models is smaller than for physical models (Pastor et al., 2003; Johnston et al., 2005). The most important and used semi-empirical predictive models are Rothermel's model (1972) and the model incorporated in the Canadian Forest Fire Behaviour Prediction System (Forestry Canada Fire Danger Group, 1992).

Statistical (empirical) models resort to information and statistical correlations obtained by fires, reproduced in laboratory or observed; all of them are used as test to calculate the descriptive parameters of the fire spread and behaviour (Albright and Meisner, 1999; Pastor et al., 2003). Evidently, each fire-test has specifical environmental conditions (wind intensity and direction, fuel types, slope, etc), so statistical relations make reference to these specific local conditions (Albright and Meisner, 1999). Since these models are not based on physical processes that regulate fire spread, their success in predicting fire behaviour is limited to conditions similar to those of test fires (Chandler et al., 1983; Catchpole and De Mestre, 1986; Perry, 1998).

Probabilistic models are based on contingency tables rather than physical or statistical equations (Albright and Meisner, 1999). In such systems, each environmental variable is associated with every possible environmental condition, and contingency tables with relative probability are created. Since numerical values for probabilities are not based on physical processes, probabilistic models are applicable only under conditions similar to those for which they were developed. They are commonly used to simulate ignition and probability of spread for a sequence of hypothetical fires over a landscape, not to predict rate of spread for a specific fire (Albright and Meisner, 1999).

6.2. Classification based on Studied Variables

This classification system refers to the type of variables studied by the fire predictive model; these models can be distinguished into (Pastor et al., 2003):

a) *Wildland fire spread models*, which provide the mechanisms to obtain the main physical variables directly related to the fire perimeter advance. The most important variables, which most models refer to, are rate of spread, fireline intensity and fuel consumption;

b) *Fire front property models*, which describe geometric flame features such as height, length, depth and angle of inclination.

6.3. Classification based on the Modelled Physical System

The most important classification scheme is based on the physical system on which modelling is developed; with this approach four categories can be distinguished. Each category represents a defined type of fire spread, tied substantially to the fuel type burned. The fire predictive models will be briefly described in the next pages.

6.3.1. Surface Fire Predictive Models

The surface fire predictive models are able to supply valid forecasts for fires spreading on surface fuels, generally with height lower than 2 m, that is small trees, shrubs, herbaceous vegetation, litter, cut residual. Many surface fires are simulated using the elliptical wave propagation technique, by which fire spreads in an approximately elliptical shape with the major axis aligned with wind direction, the maximum speed with the wind and the minimum speed into the wind; the ellipse focus is constituted by the ignition point (Johnston et al., 2005). The inputs required to evaluate the space-time evolution of fires are various according to the model: the parameters necessary to predict the surface fire behaviour (spread rate, fire front intensity, etc.) are tied to several features of environmental conditions. In Table 3, a summary of the main models developed for surface fires is proposed, although only some of them are employed successfully.

Most of these fire predictive models were theoretical and were built according to a one-dimensional, steady fireline spread hypothesis, which was represented by a combustion interface and a flat, rectangular, inclined isothermal fire front advancing across a homogeneous fuelbed (Figure 15). This fuelbed was characterized by moisture content, packing ratio and SAV ratio of its constituent particles, which were assumed to be uniformly distributed in all directions (Pastor et al., 2003). Some theoretical models differ from this approach; for example, Huang and Xie (1984) developed a model that incorporates a fuel discretisation, in order to consider the fuel characteristics not completely uniform; in Albini's model (1985; 1986) the two-dimensionality of fuel components is proposed. Cekirge (1978), Fujii et al. (1980) and Weber (1989) assume instead a non-steady propagation of the fire front, unlike the use of uniform, steady, rectangular fire front.

Table 3. Surface fire predictive models (1946-2000) (adapted from Pastor et al., 2003)

AUTHOR	MODEL TYPE	COUNTRY
Fons (1946)	Theoretical	United States
Emmons (1964)	Theoretical	United States
Hottel et al. (1965)	Theoretical	United States
McArthur (1966)	Empirical	Australia
Van Wagner (1967)	Theoretical	Canada
Thomas (1967)	Theoretical	United Kingdom
McArthur (1967)	Empirical	Australia
Anderson (1969)	Theoretical	United States
Frandsen (1971)	Semi-empirical	United States
Rothermel (1972)	Semi-empirical	United States
Pagni and Peterson (1973)	Theoretical	United States
Telisin (1974)	Theoretical	Russia
Steward (1974)	Theoretical	United States
Konev and Sukhinin (1977)	Theoretical	Russia
Cekirge (1978)	Theoretical	United States
Noble et al. (1980)	Empirical	Australia
Fujii et al. (1980)	Theoretical	Japan
Grishin et al. (1983)	Theoretical	Russia
Griffin and Allan (1984)	Semi-empirical	Australia
Huang and Xie (1984)	Theoretical	United States
Stauffer (1985)	Semi-empirical	Germany
Sneeuwjagt and Peet (1985)	Semi-empirical	Australia
Albini (1985; 1986))	Theoretical	United States
De Mestre et al. (1989)	Theoretical	Australia
Weber (1989)	Theoretical	Australia
Burrows et al. (1991)	Semi-empirical	Australia
Forestry Canada Fire Danger Group (1992)	Empirical	Canada
Croba et al. (1994)	Theoretical	Greece
Marsden-Smedley and Catchpole (1995)	Semi-empirical	Australia
Ferragut et al. (1996)	Theoretical	Spain
Grishin (1997)	Theoretical	Russia
Dupuy (1997)	Theoretical	France
Linn (1997)	Theoretical	United States
Santoni and Balbi (1998)	Theoretical	France
Catchpole et al. (1998)	Semi-empirical	Australia
Catchpole et al. (1998)	Semi-empirical	Australia
Fernandes (1998)	Semi-empirical	Portugal
Vega et al. (1998)	Semi-empirical	Spain
McCaw (1998)	Semi-empirical	Australia
Viegas et al. (1998)	Empirical	Portugal
Cheney et al. (1998)	Empirical	Australia
Porterie et al. (1998)	Theoretical	France
Larini et al. (1998)	Theoretical	France
Margerit and Sero-Guillaume (1999)	Theoretical	France
Burrows (1999)	Semi-empirical	Australia
Hargrove et al. (2000)	Probabilistic	United States
Morandini et al. (2000; 2001)	Theoretical	France
Vaz et al. (2002)	Semi-empirical	Portugal

Most theoretical models for surface fires consider radiation as the most important heat transfer process towards the unburned fuel (Pastor et al., 2003). The semi-empirical model of Rothermel (1972) is the surface fire predictive model mostly employed, and it is based on the modelling of the fire behaviour by considering the energy global balance. By the use of some information about fuels (i.e. fuel load; heat content; moisture; etc), Rothermel's model supplies the main descriptive parameters of the fire propagation.

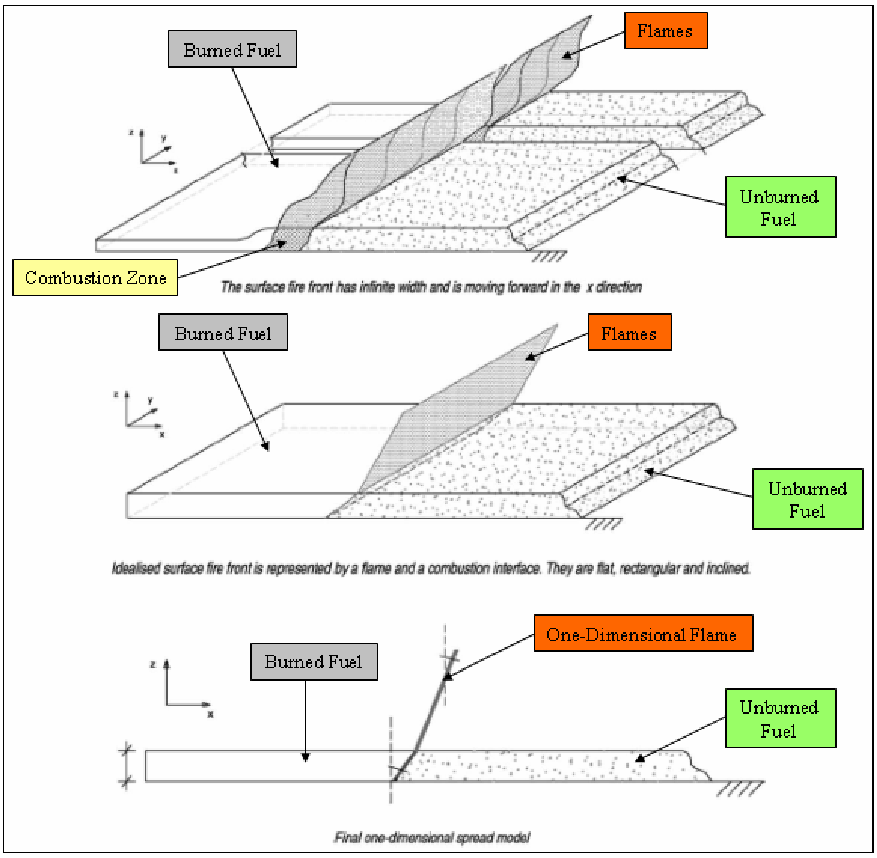

Figure 15. Modelling of surface fire front by theoretical models (adapted from Pastor et al., 2003)

6.3.2. Other Fire Predictive Models

The *crown fire predictive models* simulate the behaviour of fires spreading on aerial and surface fuels; depending on environmental conditions and on consequent rate of spread, crown fires can be active or passive. The modelling of crown fires is very complex, both for empirical or theoretical equations employed, and for the validation process; for these reasons few works have been published about crown fires. The crown fire predictive models are divided into two groups:

- crown fire initiation models;

- crown fire spread models.

Table 4 shows the main models employed for crown fires.

Hereafter the type of modelling used, the majority of crown fire models considers radiation as the major heat transfer mechanism (Pastor et al., 2003). Figure 16 defines the pattern of heat transfer by radiation during crown fires.

Table 4. Classification of crown fire predictive models (1957-2001) (Pastor et al., 2003)

AUTHOR	MODELLING	TYPE	COUNTRY
Molchanov (1957)	Initiation modelling	Semi-empirical	Russia
Kilgore and Sando (1975)	Initiation modelling	Empirical	United States
Van Wagner (1977)	Initiation modelling	Semi-empirical	Canada
Xanthopoulos (1990)	Initiation modelling	Semi-empirical	United States
Perminov (1995)	Initiation modelling	Theoretical	Russia
Alexander (1998)	Initiation modelling	Semi-empirical	Australia
Kurbatskiy and Telitsin (1977)	Spread modelling	Theoretical	Russia
Albini and Stocks (1986)	Spread modelling	Theoretical	Canada
Van Wagner (1989)	Spread modelling	Semi-empirical	Canada
Rothermel (1991)	Spread modelling	Empirical	United States
Albini (1996)	Spread modelling	Theoretical	United States
Forestry Canada Fire Danger Group (1992)	Initiation and spread modelling	Empirical	Canada
Finney (1994)	Initiation and spread modelling	Semi-empirical	United States
Grishin (1997)	Initiation and spread modelling	Theoretical	Russia
Gomes da Cruz (1999)	Initiation and spread modelling	Empirical	Canada
Scott and Reinhardt (2001)	Initiation and spread modelling	Semi-empirical	United States

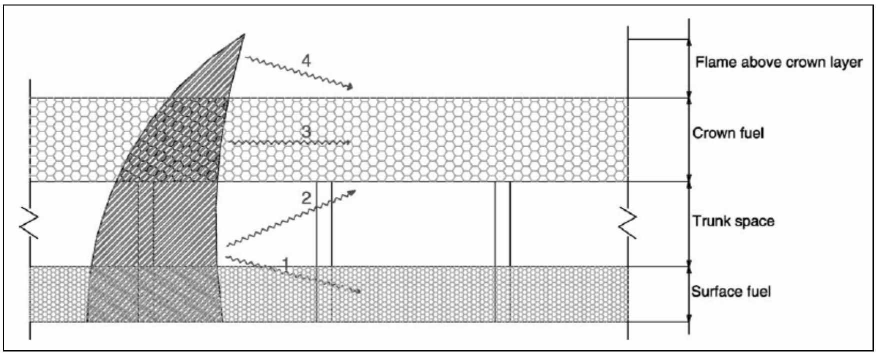

Figure 16. Simplified representation of the radiation emitted during a crown fire (from Van Wagner, 1968)

The *ground fire predictive models* are used to define the behaviour of fires that interest the ground layer, under the litter layer. Ground fires are characterized by very modest spread rate and by smoldering combustion; their impact on the ecosystem is remarkable, because the ground fires consume the organic layer of soil and heat the inorganic layer, damaging the forest biotic activities (Pastor et al., 2003). The modelling studies relative to ground fires are few, and the ground fire modelling is concentrated mainly on the probability of ignition and on the heat transfer.

The *spot fire predictive models* forecast the aerial movement of fuel firebrands, by the action of wind and of convective column, with which the fire expansion and the ignition of new fires is possible. Spot fire models are not many, and only some of these models supplied useful information to understand and predict the phenomenon. The distance that a firebrand can cover by flight and the probability of ignition of new fires are the main characteristics of spot fires that researchers investigated. The most representative works about spot fires are those of Albini (1979; 1981; 1983), who predisposed a theoretical model, partially confirmed also in empirical way. In these works, Albini defines the maximum distance that a fuel particle (with cylindrical shape) can cover, originating a new fire. The methodology is based on the employment of six separate mathematical sub-models (Table 5).

Table 5. Sub-models used by Albini (1981) in the spot fire model

SUB-MODEL	***BRIEF DESCRIPTION***
1	The structure of a steady flame that consumes the combustible pyrolyzate from the foliage
2	The structure of the steady buoyant plume established by flame, in which the particle reaches its ultimate height
3	The rate at which a woody particle burns as it moves relative t*o* atmosphere
4	The trajectory of an inert cylinder (firebrand) in the steady, non uniform, flow field of flame and buoyant plume
5	The structure of the surface wind field over rough terrain, that transports the firebrand from its maximum height to its downwind destination
6	The trajectory of a burning woody cylinder in a steady, non uniform, wind field

Viegas started new experimental activities devoted to study both the firebrand production on *Pinus* spp. cones, *Eucaliptus* spp. barks and other combustibles, and the time duration of the active firebrands. Viegas (personal communication, 2007) suggests that the spot fire problem can be modelled by considering four main phases: firebrand production (a); firebrand trajectory (b); firebrand combustion in the wind field (c); firebrand landing and ignition of new fires (d). A vertical combustion tunnel is used by Viegas and its working group in order to investigate the relationship among the different variables involved in the spot fire phenomena.

7. Fire Simulation Techniques

Each fire simulation system uses, in addition to an underlying fire prediction model, a fire simulation technique to represent the spread of fire through the landscape. The fire simulation techniques differ from each other in how they represent the landscape and the spreading process (Albright and Meisner, 1999).

The methods used for the landscape representation, obtained by GIS, are referable to two categories: the use of a lattice of discrete boxes or elements, or a continuous medium (Richards, 1995). If the landscape is shown as a lattice of discrete boxes or elements, then the spread of fire from one box to the next is governed by a specific set of rules or a probability of occurrence. If the landscape is shown as a continuous medium, the fireline shape is represented by mathematical functions (Albright and Meisner, 1999).

With the first method, when the landscape is represented as cell grid (Figure 17), the main fire simulation techniques are the bond percolation and the cellular automaton. Since a grid of cells has been used, these simulation techniques are also named *cellular propagation models*.

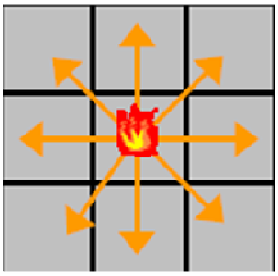

Figure 17. Cell grids in cellular propagation models

The attractiveness of using bond percolation and cellular automaton techniques to simulate the fire spread lies in the simplicity of their components for producing an overall fire behaviour that can be extremely complex (Wolfram, 1984). Moreover, both techniques yield reasonable estimates of fire spread when the fire physical determinants are unknown. In general, cellular models have had a diminishing success in reproducing the expected two-dimensional shapes and growth patterns as the environmental conditions become more heterogeneous (French, 1992). For example, cellular models have difficulty in responding appropriately to temporal changes such as shifting wind speed and direction as well as fuel moisture (Finney, 2004).

When the landscape is represented as a continuous medium, the most used simulation technique is the elliptical wave propagation. With this approach, more complex with respect to previous models, the problems affecting cellular models are avoided. The elliptical wave propagation is essentially the inverse of cellular method (Finney, 2004).

7.1. Bond Percolation

The bond percolation fire simulation technique represents the landscape as a lattice of square, triangular, or hexagonal boxes (Albright and Meisner, 1999). In each box some given values are incorporated; these values define the environmental characteristics for each landscape division.

The fire propagates from the burning boxes to the neighbouring unburned boxes with a specified probability p (Albright and Meisner, 1998). The probabilities of spread to the neighbouring boxes are adjusted to account for the preferred direction of fire spread due to external biases resulting from wind velocity, topography, differences in fuel types, etc. (MacKay and Jan, 1984; Ohtsuki and Keyes, 1986). If most of the boxes contain unburned fuel and the probability of propagation is high, then the fire spreads (percolates) throughout the lattice (Albright and Meisner, 1999).

A bond percolation technique must be tuned by adjusting the probabilities so that the modelled fire spreads in a manner comparable to that of actual fires over similar terrain under similar weather and fuel conditions. These probabilities are adjusted by an empirical fire behaviour mathematical model made using historical fire data (Pastor et al., 2003). Since the technique is not based on physical processes, success in simulating fire spread is limited to conditions similar to those for which the technique has been tuned.

7.2. Cellular Automaton

Like the bond percolation technique, the cellular automaton fire simulation technique represents the landscape as a lattice of boxes or cells, each with a set of possible values (fuel type, slope, elevation, etc.) (Albright and Meisner, 1999). Therefore, a cell has a specific initial state before ignition. The likelihood of fire spreading to each cell in the lattice is determined by rules that are the same for all cells. These rules relate the future state of cell to its initial state and the states of neighbouring cells (Albright and Meisner, 1999). The rules are based on theoretical and semi-empirical mathematical fire behaviour models. Since the rules that link fire propagation to cell grid can have a physical base, the cellular automaton technique can be applied to different environmental conditions.

7.3. Elliptical Wave Propagation

The elliptical wave propagation fire simulation technique projects the landscape as a continuous medium rather than as a lattice of boxes or cells (Albright and Meisner, 1999). Moreover, this technique is based on the use of mathematical functions and not on probabilistic calculations or logical rules. A detailed description of this fire simulation technique is proposed in the next pages.

FARSITE MODEL

FARSITE (Fire Area Simulator, Finney, 1994) is one of the main fire simulation systems developed for the description of spread and behaviour of wildland fires. This model is a deterministic simulator of the two-dimensional wildfire spread, and incorporates some models for the prediction of spread and behaviour of surface and crown fire, spotting fire, post frontal combustion, fire acceleration, fuel moisture (Finney, 2004). FARSITE is based on the semi-empirical model of fire prediction created by Rothermel (1972), and incorporated into BEHAVE Fire Behaviour Prediction and Fuel Modelling System (Andrews, 1986). The spatial growth of fire perimeters is simulated with the elliptical wave propagation technique, applying Huygens' principle (Richards, 1990; Finney, 1998).

In order to analyze the wildfire behaviour and characteristics, this simulator needs 5 essential input layers (elevation, slope, aspect, fuel models, canopy cover), inserted as digital maps with ASCII files, created by using a Geographic Information System (GIS). The complete description of the fuelbed characteristics is approximated and summarized by using fuel models; the fuel models can be standardized (Anderson, 1982; Cruz, 2005; Scott and Burgan, 2005) or customized for some distinguishing vegetation type.

FARSITE was initially developed to simulate prescribed fires in U.S. national parks and areas of naturalistic value: therefore, the simulator was tested and validated using a large number of controlled fires in these areas, with complete information of the environmental conditions (Finney, 1994; Finney and Ryan, 1995). Actually, some studies try to validate FARSITE simulator in areas different from those ones where this model was originally developed, mainly in Europe, South Africa and Australia (Van Wilgen et al., 1985; Perry et al., 1999; Sauvagnargues-Lesage et al., 2001; Dimitrakopoulos, 2002; Miller and Yool, 2002; Bilgili and Saglam, 2003; Pastor et al., 2003; De Luis et al., 2004; Arca et al., 2005, 2006): the main difficulties are linked with the differences in the fuel characteristics and with the rebuilding of weather conditions.

Rothermel's equation provides a good approximation of fire spread mainly within the range of conditions tested during calibration and development of the model, based on laboratory experiments with homogeneous fuelbed and some simplifying assumptions (Albini and Baughmann, 1979; Van Wagtedonk et al., 1996; Zhou et al., 2005a; Zhou et al., 2005b). By this way, it is possible to control many experimental conditions (fuelbed, slope, wind, humidity, etc.), but the simulation results are not always realistic.

8. FARSITE Inputs

FARSITE simulations require a set of spatial information of the three main environmental factors that affect the fire behaviour (Figure 18): topography, vegetation and meteorological conditions. All this input layers required are provided in ASCII format.

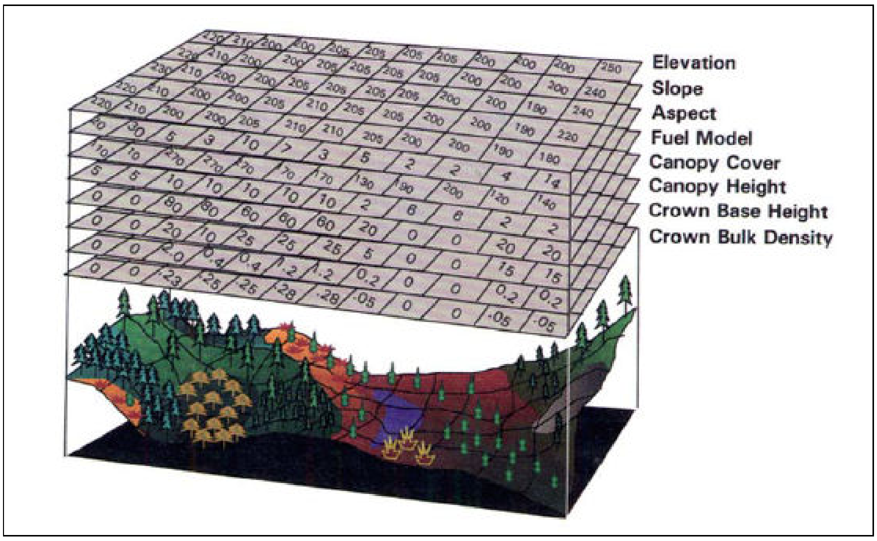

Figure 18. FARSITE input layers for landscape topography and vegetation (from Finney, 2007)

The ***topography*** factor is composed by three different layers: elevation, slope and aspect. Elevation, in meters above sea level, is used to adiabatically adjust the values of humidity and temperature, by considering a variation of these features linked with landscape elevation. Moreover elevation is necessary to compute the burned area during fire simulation in the "topography plane". Slope and aspect layers, respectively in degrees and in azimuth degrees, are used in fire spread calculation and in order to determine the hourly solar radiation incidence angle (with latitude, date and hour) and to translate the fire spread in horizontal coordinates.

The ***vegetation*** layer is composed by fuel and canopy cover maps.

The fuel model map gives a detailed physics description of the landscape surface vegetation, by using appropriate standard or custom fuel models. Each fuel model includes the following information:

- fuel load, divided in live and dead fuel load. Live fuel load is sub-divided in herbaceous and woody load, whereas dead fuel load is sub-divided by considering three timelags or size classes (1, 10, 100 hr);

- live and dead fuel 1 hr SAV ratio;

- depth of the surface fuelbed;

- dead fuel 1 hr moisture of extinction;

- live and dead fuel heat content.

For all fuel models used in FARSITE simulations, the following features have been considered as constants:

- 10 hr dead fuel SAV was 109 ft^{-1}, and 100 hr SAV was 30 ft^{-1};

- total mineral content was 5.55%, and effective (silica-free) mineral content was 1.00%;

- ovendry fuel particle density was 32 lb ft^{-3}.

The custom fuel model can be defined, inputed and managed using a specific graphical user interface (Figure 19).

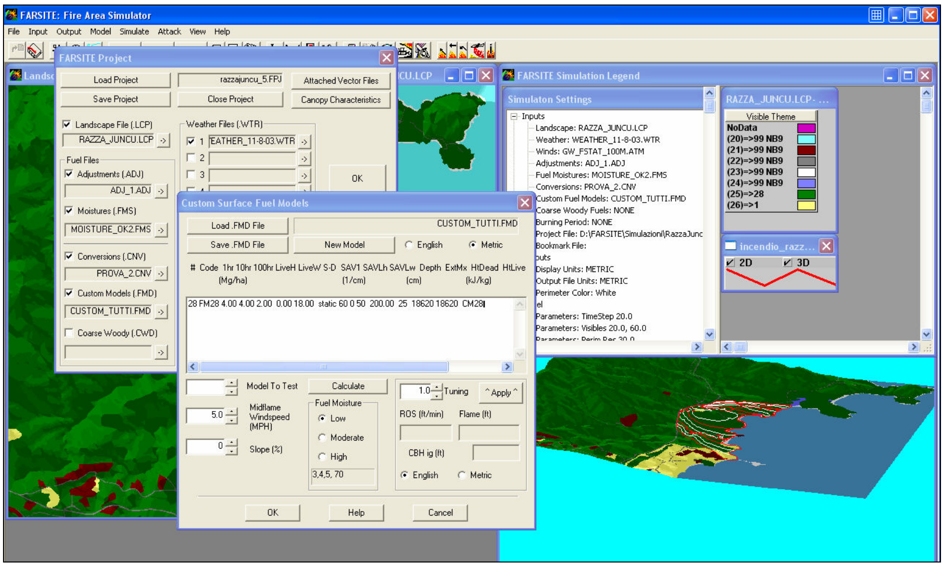

Figure 19. Graphical interface to insert custom fuel models

The canopy cover layer defines the percentage of the horizontal surface plane covered by trees. The canopy cover theme is used to determine the average surface fuel shading (Rothermel et al., 1986), that affects the fuel moisture calculations, and to calculate the wind speed reduction factor, that reduces the wind speed from the reference intensity set in the weather file to the midflame intensity (Albini and Baughman, 1979).

To the five main layers (elevation, slope, aspect, fuel model and canopy cover), the following ***optional themes*** can be added in FARSITE: stand height, crown base height, canopy bulk density, coarse woody and duff.

Stand height, expressed in meters, is used for the calculation of the wind profile. With canopy cover, it influences the wind reduction factor (Albini and Baughmann, 1979) and the firebrand behaviour during FARSITE spotting simulations (Albini, 1979).

Crown base height, in meters, is used, with surface fire intensity and foliar moisture content, to determine the threshold for transition to crown fire (Van Wagner, 1977; Alexander, 1988).

Canopy bulk density, expressed in kg m^{-3}, is necessary in order to determine the threshold for transition to active crown fire (Van Wagner, 1977; 1993).

In general, these optional layers are indispensable if forest fuels are present in the landscape (oakwoods, pine woods, etc.) and if the user needs to simulate crown fire and/or spotting fires to determine the wildfire behaviour in these conditions.

Duff load theme, used in order to define the duff load, and commonly expressed in t ha^{-1} cm^{-1}, is necessary to determine the ground fire behaviour with the Post Frontal Combustion model used in FARSITE.

Also the coarse woody debris theme is used to determine the ground fire behaviour with the Post Frontal Combustion model. The coarse woody debris is constituted by 1000 hr sound and rotten fuels.

The five indispensable layers, and eventually the other optional themes, constitute in FARSITE the "Landscape File (.lcp)", which contains all the landscape spatial information. The graphical interface is below proposed (Figure 20).

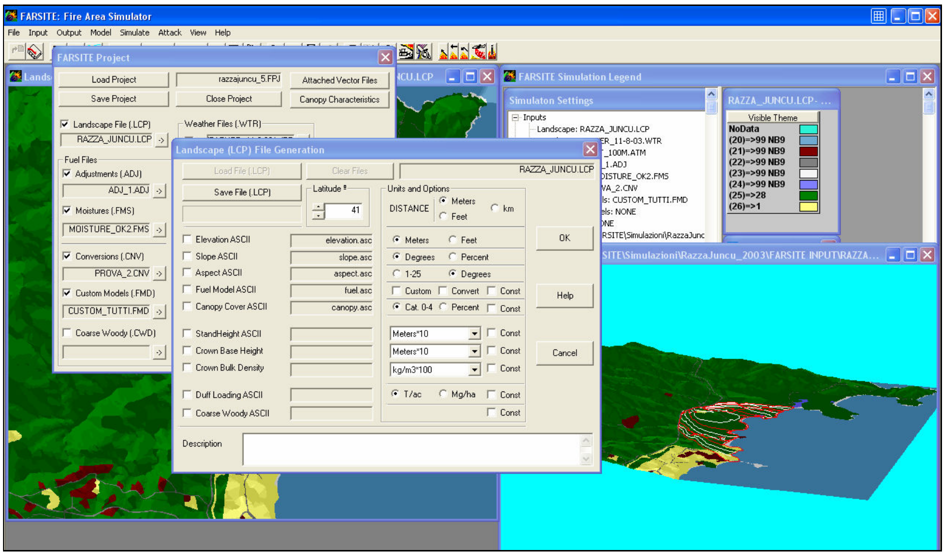

Figure 20. Definition of the landscape file

The ***fuel moisture*** data define the water content of each fuel model, before the event. In this file (.FMS), the fuel moisture must be set for dead (1 hr, 10 hr, 100 hr) and live (herbaceous and woody) components.

FARSITE considers as constant in space and time the values of live fuel moisture (unless manual changes), whereas dead fuel moisture can change. For this reason, in the simulations a "conditioning period" before the wildfire day can be used. With this tool, FARSITE calculates the dead fuel moisture content changes: the effect of the initial moisture content of dead fuels decreases if the conditioning period increases. To evaluate this trend, FARSITE uses the BEHAVE model (Rothermel et al., 1986; Hartford and Rothermel, 1991) for the 1 hr and 10 hr dead fuel moisture, and the National Fire Danger Rating System equations (Bradshaw et al., 1984) for the 100 hr dead fuel moisture.

FARSITE graphical interface for fuel moisture is shown in Figure 21.

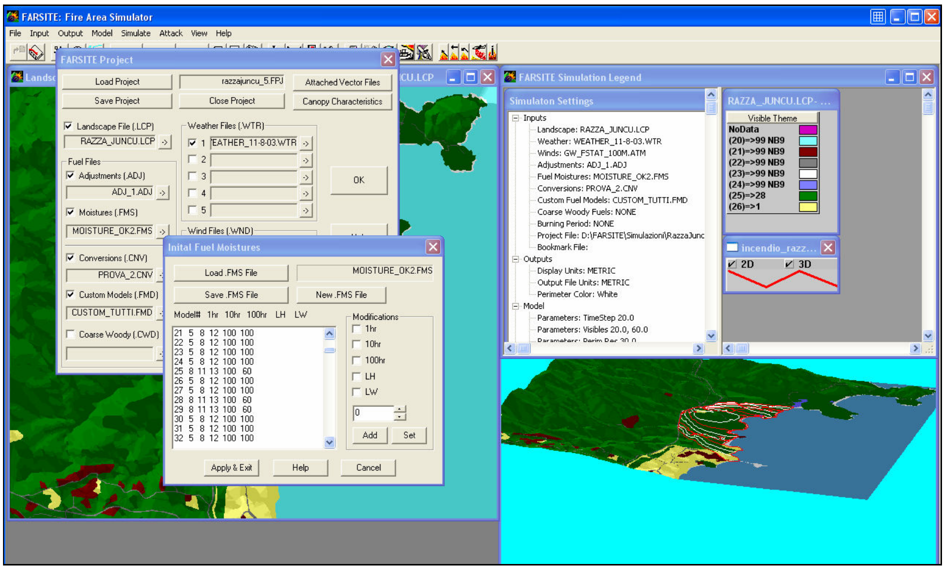

Figure 21. Graphical interface for fuel moisture file

The ***meteorological conditions*** of the wildfire days are considered by a weather file (.WTR). This file contains daily observations on temperature, hours at which minimum and maximum temperature were recorded, humidity and precipitation. The meteorological data are used to define a diurnal weather pattern for a designated portion of the landscape so that dead woody fuel moistures can be calculated (Finney, 2004). Temperature and humidity are assumed to respond inversely over time as approximated by a cosine curve between maxima and minima (Beck and Trevitt, 1989; Rothermel et al., 1986) (Figure 22).

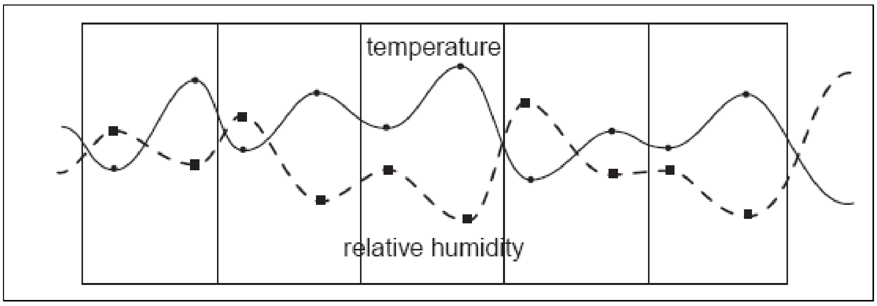

Figure 22. The diurnal pattern of temperature and humidity, by using minimum and maximum values from the weather file

Therefore, FARSITE fits the temperature and humidity data to a sine curve form for interpolation of these parameters throughout the day cycle. Using these weather data and the starting fuel moistures, the model provides dynamic inputs of weather and fuel moistures over the simulation time.

Adiabatic adjustment from input elevations to any landscape point determines the local temperature (1 °C per 100 m) and humidity (0.2 °C per 100 m); the possible rainfall is assumed spatially constant.

The weather file is inserted in FARSITE as ASCII file, as presented in Figure 23.

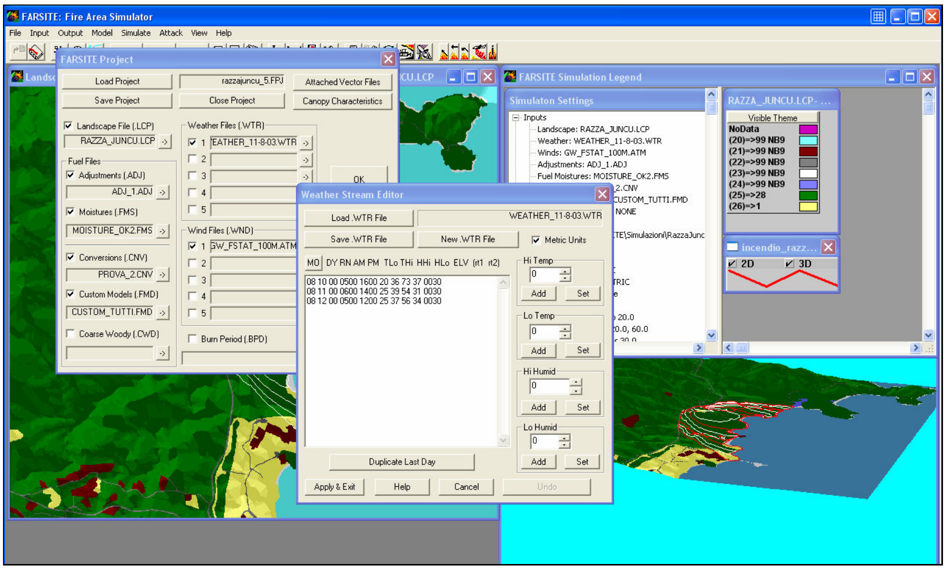

Figure 23. The weather file production in FARSITE

The ***wind data*** inserted in FARSITE are required at 6.1 m above the top of vegetation. The wind file (.WND, or .ATM when gridded files are used) is composed by three hourly data: wind speed, wind direction and cloud cover. The wind vectors can be inserted as constant for all the landscape, otherwise the landscape can be divided into a mixture of cells, each one with a defined wind stream. The same procedure (constant or gridded stream) is applicable to supply more detailed weather condition files, in the weather file.

The wind intensity is assumed parallel to the ground and is reduced till the midflame height (this wind intensity is named "effective" midflame wind speed, *U*; Albini and Baughman, 1979), without any account for different wind exposures to surface fires that result for combinations of wind direction and topographic position (such as ridgetop versus sideslope versus valley bottom) (Albini and Baughman, 1979; Andrews, 1986). For non-forested areas, as for Mediterranean maquis, the midflame wind speed is reduced to a nominal height equal to twice fuelbed depth (Albini and Baughman, 1979). In forested areas the wind speed is reduced locally by the canopy cover data provided as spatial theme (Finney, 2004):

$$U = \frac{0.555U_{20+H}}{\left(f\,3.28H\right)^{1/2} \ln\left[\frac{\left(20+1.18H\right)}{0.43H}\right]} \quad (3)$$

where H is the forest canopy height (m), derived from spatial inputs; U_{20+H} defines the wind speed (m s^{-1}) at 6.1 m above the tree tops; f is the crown filling fraction, calculated as:

$$f = \frac{C}{100} \times \frac{\pi}{12} \quad (4)$$

where C is the canopy cover value of the landscape cells. This equation assumes conical tree crowns, occupying one-third the volume of a cylinder of the same dimensions (Albini and Baughmann, 1979).

For all the simulations, an ***adjustment factor*** is considered. The adjustment factor file (.ADJ) allows to use estimated or observed data to tune the simulated rate of spread for a specific fuel model. In any case, with the adjustment factor only the fire rate of spread can be modified.

Before the run of a simulation, other elements are indispensable in order to define the fire environment and behaviour.

The first element is named "***Parameters***", and it is characterized by three components:

a) timestep (and visible timestep), which defines the maximum amount of time for which the conditions are assumed constant at a given point;

b) perimeter resolution, which defines the maximum spacing of projection points in the fire perimeter. The reduction of the perimeter resolution induces an increment in the fire projection points.

c) distance resolution, which defines the maximum distance of travel in a timestep without the need of new information from the landscape.

The second element is the "***Fire Behaviour Options***", with which it is possible to set the fire behaviour characteristics. For example, with this tool the user can choose to simulate a crown fire or a "simple" surface fire, or to define the ignition frequency and the delay of new fronts generated by firebrands.

The last element is the "***Duration***", which defines the starting and stopping time for fire simulation and fuel moisture calculations. In this box, the use of a conditioning period for the fuel moisture calculations can be chosen.

All the simulations made by FARSITE can be exported and managed by using a GIS: some ***Outputs*** are exported as vector, other as raster format. The typical vector file produced by FARSITE simulations is the fire perimeter shapefile, which contains the vertices of each timestep fire polygons. Raster outputs are produced by FARSITE for eight fire behaviour parameters; these files have a default ASCII format, and their resolution can range between 1 and 200 meters. The eight raster files are presented in the Table 6.

Table 6. The eight output files produced by FARSITE

OUTPUT FILE	***EXTENSION***	***VALUE UNITS***
Time of Arrival	.TOA	hours
Fireline Intensity	.FLI	$kW\ m^{-1}$
Flame Length	.FML	m
Rate of Spread	.ROS	$m\ min^{-1}$
Heat per Unit Area	.HPA	$kJ\ m^{-2}$
Reaction Intensity	.RCI	$kW\ m^{-2}$
Crown-No Crown	.CFR	1=surface, 2=passive, 3=active
Spread Direction	.SDR	0-359° Azimuth

9. FARSITE Propagation Technique

Two-dimensional fire shapes are assumed to be generally ellipsoidal under uniform conditions. Uniform conditions occur when factors affecting fire behaviour (fuels, weather, topography) are spatially and temporally constant, although these conditions rarely exist in nature (Finney, 2004) (Figure 24).

Figure 24. During a prescribed fire with punctual ignitions, under uniform conditions, the shape of fire is typically ellipsoidal (Marinha Grande Pinewood, Portugal, February 2007)

Many studies have shown that a fire spreading in landscapes with uniform and constant fuel conditions, and with constant slope, wind and fuel moisture, tends to assume a simple ellipse shape (Richards, 1990). Observations under relatively uniform field conditions have suggested fire shapes ranging from ovoid (Peet, 1967) to pair of ellipses (Albini, 1976; Anderson, 1983), to fan shaped (Byram, 1959). Most of the disparity between simple ellipse and alternate shapes occur towards the rear of fire, where little area is burned compared to the heading portions (Finney, 2004). Even if the assumption of elliptical fire shapes in continuous fuels is true, fire shapes in fuels that are not continuous at the scale relevant to mechanisms of fire propagation may not be elliptical or intuitive (Green, 1983).

Green et al. (1983) concluded that a simple ellipse can fit observed fire growth data as well as other shapes, in relation with environmental conditions. Richards (1990) analytically developed a set of differential equations in order to describe the fire propagation, by the expansion of an elliptical wave front, in non-uniform environmental conditions. Shape and size of ellipses are dependent upon some parameters and characteristics based on the Fire Behaviour Prediction System of Forestry Canada Fire Danger Group (1992). The fire can propagate with a different elliptical shape when the burning conditions change (i.e., for wind speed or slope variation) (Finney, 2004). Actually, laboratory experiments (McAlpine, 1989) suggest that these shape changes occur relatively rapidly and at a short distance compared to the time and distance required for the build-up in spread rate or intensity. The elliptical wave technique requires no local tuning, assuming that fuels, weather and topography in the area of interest are sufficiently similar to those for which the underlying parameters were recorded. However, this technique should not be used under conditions for which representative parameters are not available (Albright and Meisner, 1999).

FARSITE simulates the fire spread by using the elliptical wave propagation technique, but a set of implementations and perfectings are used; therefore, there are some differences with respect to Huygens' original principle. With this fire growth modelling, the fire front is propagated as a continuously expanding fire polygon at specified timesteps (Anderson et al., 1982). On the basis of Huygens' principle approach, Anderson et al. (1982) proposed the definition of a number of regularly spaced points, or vertices, on the fire perimeter: each point is the ignition site of a small fire that spreads outward from the point. The two-dimensional vertices, defined by X and Y coordinates, represent the fire perimeter growth points, with Richards' technique (1990; 1995). The number of vertices increases as fire grows over time (as polygon expands) (Figure 25).

The fire perimeter for each timestep is formed by the union of small ellipses that propagate from single vertices. The expansion of the fire polygon is determined by computing spread rate and direction from each vertex and multiplying by the duration of timestep (Finney, 2004). As next equations show, the shape and direction of ellipses are determined by wind-slope vector, while the size is determined by spread rate and length of timestep (Finney, 2004). Ellipse shape, direction and dimensions are therefore tied to environmental conditions (Figure 26). For example, many studies state that the fire eccentricity increases with the increment of wind speed or slope steepness, or both (Alexander, 1985).

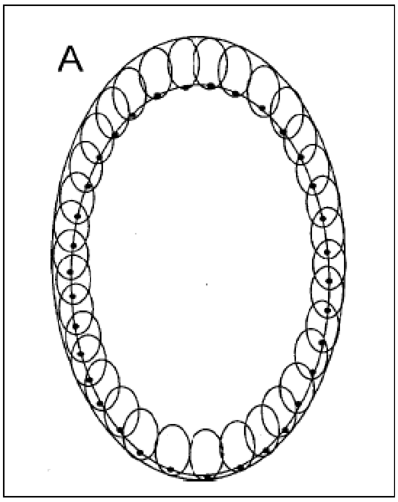

Figure 25. The growth of the polygon for each fire perimeter point, with homogeneous environmental conditions (Finney, 2004)

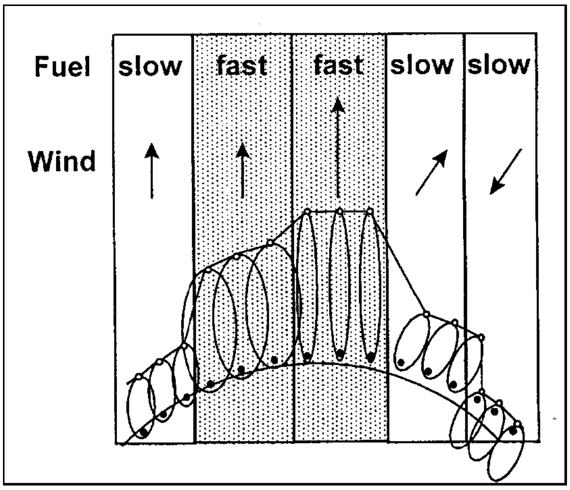

Figure 26. The effect of different environmental conditions (fuel and wind) on the ellipse eccentricity (Finney, 2004)

Spread direction and rate normal to fire front is determined by direction and rate of maximum spread by an elliptical transformation (Richards, 1995). The reliance on an assumed fire elliptical shape is necessary because the spread rate of only the heading portion of a fire is predicted by the present fire spread model (Rothermel, 1972). Fire spread in all other directions is inferred from the forward spread rate using the mathematical properties of ellipse (Finney, 2004).

It is common to assume that the ignition point or the fire origin is coincident with the rear focus of the ellipse (Alexander, 1985; Bratten, 1978). Although not necessarily correct (Bilgili and Methven, 1990; Catchpole et al., 1982; Green et al., 1983) this does provide an implicit backing fire spread rate (Alexander, 1985). Alternatively, the location of the fire origin along the major axis of ellipse could be computed from an independently calculated backing spread rate (Finney, 2004).

As discussed before, FARSITE uses Richards' method (1990; 1995) in order to compute the fire polygon growth with an elliptical approach. Richards' differential equations describe the expansion of an elliptical wave front from a series of vertices that define the edge of the fire. The information required at each vertex are:

i) the orientation of the vertex on fire front in terms of component differentials (m) x_s e y_s;

ii) the direction of maximum fire spread rate θ (by considering the resultant wind-slope vector; radians azimuth);

iii) the shape of an elliptical fire, determined by the conditions which characterize that vertex, in terms of dimensions *a*, *b*, *c* (m min^{-1}) (Figure 27).

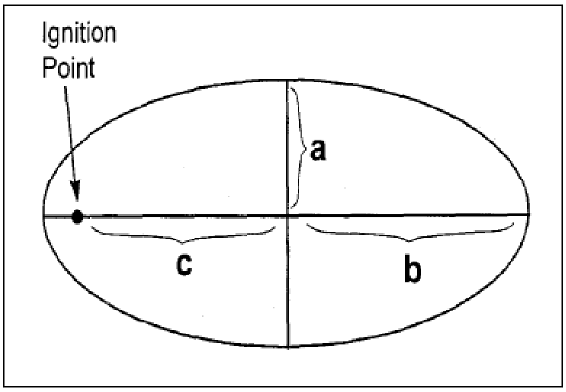

Figure 27. The elliptical wave propagation for each fire perimeter vertex; *a* corresponds to 1/2 the minor axis, *b* corresponds to 1/2 the major axis, *c* identifies the distance from ignition point (ellipse fire) to center of ellipse (Finney, 2004)

From these inputs, Richards' (1990) equation computes the orthogonal spread rate differentials (m min^{-1}) X_t and Y_t for a given vertex (Finney, 2004):

$$X_t = \frac{a^2 \cos\theta(x_s \cos\theta + y_s \cos\theta) - b^2 \sin\theta(x_s \cos\theta - y_s \sin\theta)}{(b^2(x_s \cos\theta - y_s \sin\theta)^2 + a^2(x_s \sin\theta + y_s \cos\theta)^2)^{1/2}} + c \sin\theta \qquad (5)$$

$$Y_t = \frac{-a^2 \sin\theta(x_s \sin\theta + y_s \cos\theta) - b^2 \cos\theta(x_s \cos\theta - y_s \sin\theta)}{(b^2(x_s \cos\theta - y_s \sin\theta)^2 + a^2(x_s \sin\theta + y_s \cos\theta)^2)^{1/2}} + c \cos\theta \qquad (6)$$

Richards' (1990, 1995) equations were originally developed for flat terrain. In these terrains a horizontal coordinate system remains unchanged when projected onto the ground surface. This is not the case for sloping terrain (Finney, 2004). All inputs and outputs associated with equations 5 and 6 are referred to coordinates of the surface plane local for each vertex (x_i, y_i). The computer stores all vertices in the horizontal plane, so inputs to equations 5 and 6 (x_s, y_s e θ) must be transformed to surface plane, and outputs (X_t, Y_t) must be transformed to horizontal plane (Figure 28).

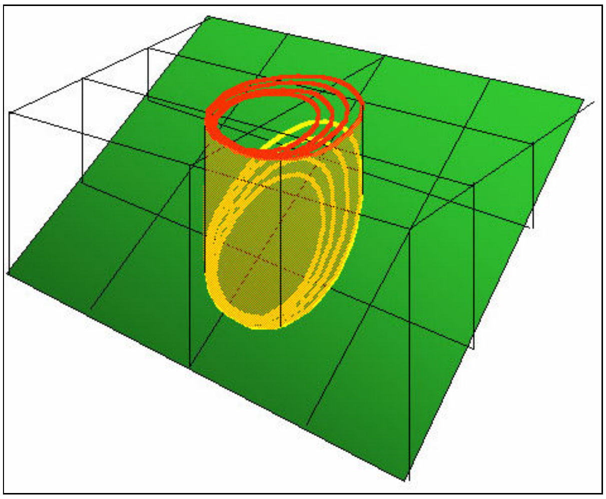

Figure 28. Transformation of the surface fire perimeter from horizontal to surface ground plane (from Finney, 2007)

For a complete discussion about the transformations of Richards' equations for sloping terrain, it can be useful to read Finney (2004).

The dimensions *a*, *b*, *c* for equations 5 and 6 describe the elliptical shape assumed by the fire produced at a given vertex or ignition point (Finney, 2004). Alexander (1985) assumes that the effects of wind and slope on fire shape are proportional to their effect on the rate of spread of the heading fire (Figure 29). Fire shapes have only been determined empirically and with respect to measured wind speed, but shapes may be affected differently by wind and slope (Finney, 2004). The fire shape is computed at each vertex of the perimeter using the "effective" midflame wind speed (U, in m s^{-1} (equation 3 for forested areas)), which is obtained from the reduction of the wind intensity at 6.1 m above the tree tops, as already pointed out previously. For surface fires, the perimeter of the spreading fire is obtained from the resultant vector of midflame wind and slope (as presented in equations 26 and 27).

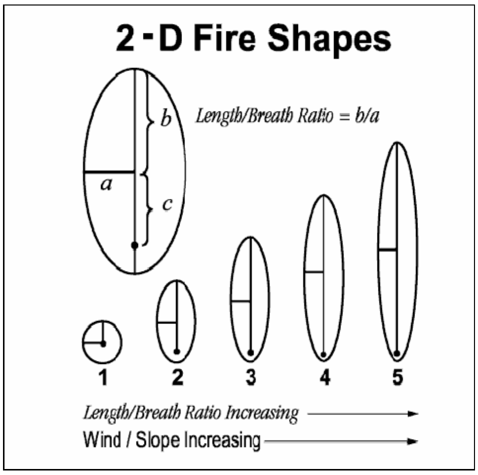

Figure 29. Slope and wind effect on fire shape (from Finney, 2004)

The dimensions of elliptical fires have been related to wind speed using a number of empirical formulas (Alexander, 1985; Andrews, 1986; Bilgili and Methven, 1990; Rothermel, 1991; Forestry Canada Fire Danger Group, 1992). These formulas produce various fire shapes for a given wind speed (Finney, 2004). The range and uncertainty in wind speed over time and with vertical height, forest structure, and uneven terrain, accounts for at least as much variation in fire shape as any of the individual models (Finney, 2004). For FARSITE, the relationship developed by Anderson (1983) was chosen for the length to breadth ratio (*LB*) assuming fire grows as a single ellipse (Alexander, 1985):

$$LB = 0.936e^{(0.2566U)} + 0.461e^{(-0.1548U)} - 0.397 \quad (7)$$

The original equation of Anderson (1983) was modified by subtracting 0.397 from *LB*, to have *LB* = 1.0 on flat terrain with absence of wind (Finney, 2004). The accuracy in the prediction of the fire growth has a benefit because the natural variation in wind direction at high frequencies effectively decreases *LB* during real fires (Simard and Young, 1978; Richards, 1993). Considering the empirical data referenced by Alexander (1985), ellipses with *LB* values greater than 8.0 in the equation 7 are truncated to that "threshold" dimension. Assuming the rear focus of ellipses to be the fire origin (Alexander, 1985), the head to back ratio is described as:

$$HB = \left[LB + \frac{LB^2 - 1}{LB} - (LB^2 - 1) \right]^{1/2} \quad (8)$$

from which the *a*, *b*, and *c* dimensions of the elliptical axes (equations 5 and 6) can then be computed in units of fire rate of spread *R* (m min-1):

$$a = 0.5\left(\frac{R + \frac{R}{HB}}{LB}\right) \quad (9)$$

$$b = 0.5\left[R + \frac{R}{HB}\right] \quad (10)$$

$$c = b - \frac{R}{HB} \quad (11)$$

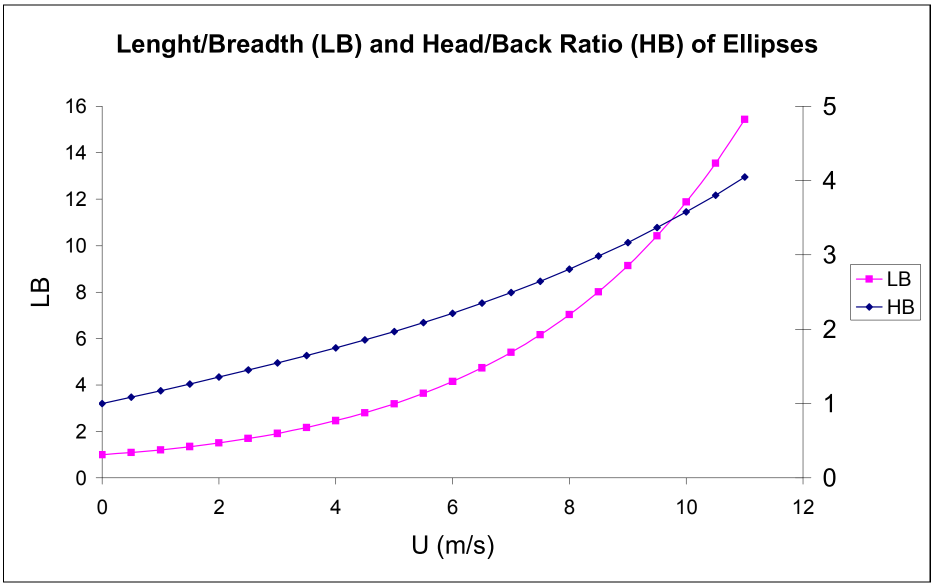

Figure 30. The wind speed effect on the elliptical fire shape, for LB and HB ratios

10. FARSITE Fire Behaviour Models

Fire behaviour models used in FARSITE are specific to distinct "types" of fire behaviour: for this reason, separate models are used for surface fire, crown fire, spotting, post frontal combustion and point-source fire acceleration. Fire behaviour models are formulated as one-dimensional point calculations: they produce outputs from conditions specified at a defined geographic point. By using Huygens' principle approach, the wave-front is based on a set of vertices, from which data on fire environment are obtained. At each vertex, the environmental variables (fuels, weather and topography) are used to compute fire behaviour.

The fire spread in time, with the elliptical wave technique, is evaluated and parameterized at each vertex by using the previous equations.

The linkage among the fire behaviour models in FARSITE relies on an assumed sequence of fire activity (Finney, 1998). In the first moments, a fire may spread as a surface fire, burning grass, shrubs, or downed woody fuels in contact with the ground surface. If the environmental conditions permit, the fire will accelerate towards a new equilibrium spread condition. Given sufficient fuels, weather, and topography, the fire may make the transition to crown fire. If crown fuels are ignited, trees are assumed to torch and can loft embers. The following models were used in FARSITE to represent these phases of fire activity.

10.1. Rothermel's Surface Fire Spread Model

The surface fire spread model used in FARSITE is Rothermel's fire spread equation (Albini, 1976; Rothermel, 1972). Rothermel's model is a semi-empirical model developed essentially from results obtained on a quite considerable amount of experiments. In simple terms, Rothermel's model has been developed in order to determine the propagation of a two-dimensional steady surface fire, burning homogeneous fuelbed, with uniform slope and wind conditions (André et al., 1992). The main outputs produced by Rothermel's fire spread equation are the rate of spread R and the reaction intensity I_r of surface fires.

The ***surface fire rate of spread R*** (m min^{-1}) is calculated at each vertex of the fire polygon, burning in stationary regime and spreading on a plane parallel to the ground surface; several environmental conditions are used as input. Rothermel's equation (12) expresses an energy balance within a unit volume of the fuel ahead of the flame, and it represents the ratio between the rate of fuel heating and the energy required to bring that same fuel to ignition (Lopes, 2000). In more simple terms, the numerator is the total heat released by fire, while the denominator is the heat that the fuel is able to absorb. In Rothermel's equation the numerator, that represents the global heat released by combustion, can be divided in three parts (André et al., 1992):

- the first component represents the heat released in environmental conditions of no slope and no wind; therefore this component is only dependent on reaction intensity I_r and on propagating flux ratio π. For these reasons, with no slope and no wind the rate of spread is exclusively determined by fuelbed and by the characteristics of fuel particles;

- the second part defines the effect of the adimensional factor Φ_w, linked with wind speed and with fuelbed and fuel particle geometry;

- the last component defines the effect of the adimensional factor Φ_s, dependent on slope of terrain and on fuelbed geometry.

Rothermel's fire spread equation is calculated as:

$$R = \frac{I_r \pi (1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}} \qquad (12)$$

where:

✓ R = rate of spread (in m min^{-1}), i.e. the forward rate of propagation of the surface fire front, in stationary conditions;

✓ I_r = reaction intensity (in kJ min^{-1} m^{-2}), i.e. the energy release rate per unit area of flame front;

✓ π = propagating flux ratio (dimensionless), i.e. the fraction of energy released responsible for neighbouring fuel heating and ignition;

✓ ρ_b = bulk density (in kg m^{-3}), i.e. the dry mass of fuel per unit volume;

✓ ε = effective heating number (dimensionless), i.e. the ratio between the bulk density and the mass of fuel involved in the process of ignition;

✓ Q_{ig} = heat of pre-ignition (in kJ kg^{-1}), i.e. the heat required to bring the unit weight of fuel to ignition.

Φ_w and Φ_s coefficients, related respectively to wind and slope, are considered in additional terms on Rothermel's equation, and are calculated as defined in the equation 27 and 26.

In order to define all the features of Rothermel's model, a series of equations, defined in the BEHAVE format, are indispensable (Albini, 1976; Anderson, 1982; Burgan and Rothermel, 1984; Andrews, 1986). First of all, some variables describing the fuel characteristics, indispensable to determine the values of the various equations, are added in FARSITE fuel models as input*. Therefore, the values of these variables are known, because the user needs to set them before the simulation:

- W_O = fuel load (in kg m^{-3});
- δ = fuel depth (in m);
- β = packing ratio (dimensionless);
- σ = SAV (surface/volume) ratio (in m^{-1});
- ρ = particle density (in kg m^{-3});
- M_f = fuel moisture content (in % of dry weight);
- M_x = moisture of extinction (in % of dry weight);
- h = fuel heat content (in J kg^{-1});
- S_t = fuel mineral content (in %);
- S_e = fuel mineral content, silica-free (in %)

The ***reaction intensity*** I_r quantifies the rate of released energy per unit area of fire front, and it is evaluated by the following equation:

$$I_r = \Gamma' W_n h \eta_m \eta_s \quad \text{(in W m}^{-2}\text{)} \qquad (13)$$

The reaction intensity is computed as function of the net fuel load W_n (expressed in kg m^{-2}), the optimum reaction velocity Γ' (in s^{-1}) and the inferior caloric power of fuel h (in kJ kg^{-1}). The effects of moisture and mineral content on reaction intensity are introduced through parameters η_m and η_s (named respectively moisture damping coefficient and mineral damping coefficient).

The optimum reaction velocity Γ' is the inverse of the time a fuel particle would take for complete combustion, with no moisture and no mineral content. This feature is computed by the following equation:

* Most fuel properties are supplied for different fuel size classes and dead-live classification. Most properties are averaged between size classes using the surface area as the weighting factor, as suggested by Rothermel (1972). Dead and live fuels are treated separately, each being used to compute its own value. Final value for some equations is obtained as sum of corresponding values for dead and live fuel.

$$\Gamma' = \Gamma'_{max} \left(\frac{\beta}{\beta_{op}} \right)^{A} e^{\left[\frac{A(1-\beta)}{\beta_{op}} \right]} \quad \text{(in min}^{-1}\text{)} \tag{14}$$

and it is proportional to the maximum reaction velocity Γ'_{max} (in s^{-1}), which is calculated by considering the SAV ratio σ of fuel particles:

$$\Gamma'_{max} = \left(0.0591 + 2.926\sigma^{-1.5}\right)^{-1} \quad \text{(in min}^{-1}\text{)} \tag{15}$$

For the calculation of the optimum reaction velocity Γ', the packing ratio β and the optimum packing ratio β_{op} are also important. The equations for the evaluation of the packing ratio β and the optimum packing ratio β_{op} are respectively:

$$\beta = \frac{\rho_b}{\rho_p} \quad \text{(dimensionless)} \tag{16}$$

$$\beta_{op} = 0.20395\sigma^{-0.8189} \quad \text{(dimensionless)} \tag{17}$$

In equation 16, for the evaluation of the fuel packing ratio, ρ_b and ρ_p represent respectively the fuel array bulk density (Rothermel, 1972) (in kg m^{-3}) and the fuel particle density (in kg m^{-3}). The ovendry bulk density ρ_b will be defined in equation 23.

The other element that affects the optimum reaction velocity value Γ' is the A coefficient, computed as:

$$A = 8.9033\sigma^{-0.7913} \quad \text{(dimensionless)} \tag{18}$$

As it was before defined, η_m and η_s permit to evaluate respectively the moisture effect and the mineral content of fuel particles on reaction intensity I_r; a proportional relationship among I_r, η_m and η_s exists. The equations for the evaluation of the moisture damping coefficient η_m and of the mineral damping coefficient η_s are:

$$\eta_m = 1 - 2.59\frac{M_f}{M_x} + 5.11\left(\frac{M_f}{M_x}\right)^2 - 3.52\left(\frac{M_f}{M_x}\right)^3 \quad \text{(dimensionless)} \tag{19}$$

$$\eta_s = 0.174 S_e^{-0.19} \quad \text{(dimensionless)} \tag{20}$$

Finally, for the evaluation of the optimum reaction velocity Γ', the net fuel load W_n (in kg m^{-2}) is considered; the value of the net fuel load W_n is in inverse relation with the fuel particle mineral content:

$$W_n = W_0(1 - S_t) \quad \text{(in kg m}^{-2}\text{)} \tag{21}$$

To evaluate the fire rate of spread R it must be defined the propagating flux ratio π, which represents the ratio of energy released responsible of fuel heating and ignition:

$$\pi = (192 + 7.9095\sigma)^{-1} e^{\left[\left(0.792+3.7597\sigma^{0.5}\right)(\beta+0.1)\right]} \quad \text{(dimensionless)} \qquad (22)$$

The propagation flux ratio π defines the ratio of energy transmitted to fuel in conditions of no wind and no slope. The numerical value of the propagation flux ratio is linked both with the packing ratio β and with the SAV ratio σ.

ρ_b represents the ovendry fuel bulk density (in kg m^{-3}), which defines the fuel dry mass per unit of volume. The value of the bulk density is computed by the ratio of fuel load (kg m^{-2}) to surface fuel depth (m)

$$\rho_b = \frac{W_0}{\delta} \quad \text{(in kg m}^{-3}\text{)} \qquad (23)$$

ε defines the effective heating number, which is used in order to determine the efficiency of heating as a function of the particle size, and it represents the fuel amount heated up to the ignition temperature. The effective heating number value (Frandsen, 1973) is linked with the SAV ratio of the fuel particles:

$$\varepsilon = e^{\left(-\frac{4.528}{\sigma}\right)} \quad \text{(dimensionless)} \qquad (24)$$

Finally, to compute the rate of spread in Rothermel's equation the evaluation of the heat of pre-ignition Q_{ig} is necessary. This element defines the heat required to bring a unit weight of fuel to ignition:

$$Q_{ig} = 581.092 + 2594 M_f \quad \text{(in kJ kg}^{-1}\text{)} \qquad (25)$$

The heat of pre-ignition is computed with the assumption that the fuel ignition temperature T_{ig} is 320 °C, and that the fuel moisture M_f is completely evaporated when a temperature of 100 °C is reached (André et al., 1992). Evidently, the heat of pre-ignition is strongly linked with the initial fuel moisture M_f.

The symbol θ in Richards' equations represents the angle of the wind-slope vector for the direction of maximum fire spread ($0 \le \theta \le 2\pi$) on the local slope at a given vertex (x_i, y_i) (Finney, 2004). This vector was calculated for surface fires using two elements: the dimensionless coefficients for midflame wind speed Φ_w and slope Φ_s (Rothermel, 1972; Wilson, 1980):

$$\Phi_s = 5.275\beta^{-0.3} \tan\phi^2 \quad (26)$$

$$\Phi_w = C(3.281U)^B \left(\frac{\beta}{\beta_{op}}\right)^{-E} \quad (27)$$

where $\varnothing$ is the terrain slope (radians), U is the midflame wind speed (m s^{-1}), and C, B, and E coefficients are functions of the fuel particle sizes in the fuelbed (Burgan, 1987; Rothermel, 1972).

The vectors used in order to determine the spread direction of surface fires are highly dependent on the characteristics of surface fuelbed, and thus they are not necessarily applicable to determine the spread direction of active crown fires.

Another important element is the ***fireline intensity I_b*** (Byram, 1959), that defines the heat released per second from a unit section of fuel extending from the front to the back of the flaming zone:

$$I_b = \frac{HW_nR}{60} \quad \text{(in kW m}^{-1}\text{)} \quad (28)$$

where H is the total heat released by fuel (the total heat produced except the heat required for fuel moisture evaporation), W_n is the net fuel load burned with flaming combustion*, and R is the fire spread rate.

The heat released per surface unit HPA is the product of the total heat released by fuel H and the net fuel load W_n. Therefore, HPA is equal to HW_n of Byram's equation 29. HPA can be defined also as (Andrews and Rothermel, 1982):

$$HPA = I_r t_r \quad \text{(in kJ m}^{-2}\text{)} \quad (29)$$

where I_r represents the reaction intensity (in kJ min^{-1} m^{-2}) and t_r is the residence time (in min). The residence time t_r is computed as (Anderson, 1969):

$$t_r = \frac{12.595}{\sigma} \quad (30)$$

where σ is the SAV ratio (cm^{-1}) of the fuelbed.

Since HW_n is equal to HPA, the W_n term can be computed also as:

$$W_n = \frac{HPA}{H} \quad (31)$$

* the total amount of fuel burned with following smoldering and glowing combustion is not considered (Scott and Reinhardt, 2001).

In FARSITE and BEHAVE, the fireline intensity I_b is computed by using the following equation (Wilson, 1980; Finney, 2004):

$$I_b = \frac{I_r}{60} \times \frac{12.595R}{\sigma} \Leftrightarrow I_b = \frac{I_r t_r R}{60} \qquad (32)$$

In general terms, in FARSITE the frontal fire characteristics (spread rate, fireline intensity, and so forth) are calculated for a steady-state fire, and are dependent on the current environmental conditions. All of these environmental parameters must be available or computable at any point on the landscape at any time (Finney, 2004).

10.2. Other Models

FARSITE *crown fire model* was developed by Van Wagner (1977, 1993) and it is similar to its implementation in the Canadian Forest Fire Behaviour Prediction System (Forestry Canada Fire Danger Group, 1992). It determines if the fire remains burning in surface fuels or makes a transition to burning in crown fuels, and whether it spreads actively through tree crowns or simply torches individual trees (Finney, 2004). The model assumes that a threshold for transition to crown fire I_o (kW m^{-1}) exists: this value is dependent on the crown foliar moisture content M (percent on dry weight basis) and on the height to crown base CBH (m) (Van Wagner, 1989). Transition to crown fire occurs if the surface fire intensity I_b meets or exceeds I_o. In the last versions of FARSITE, another crown fire model has been added, by using Scott and Reinhardt's (2001) methodology. Therefore, actually a user can choose to simulate crown fire behaviour by using the "classic" FARSITE method or Scott and Reinhardt's (2001) method. In general terms, Scott and Reinhardt's method is a crown fire prediction system useful mainly when crown fire interests wide areas (Finney, 2004).

The *spotting model* used in FARSITE is based on Albini's (1979) equations for spotting from torching trees. Spotting distance in uneven terrain depends on ember size, vertical wind speed profile, and surface topography in the direction of the ember travel (Finney, 2004). In general, larger embers can burn longer and can achieve a higher terminal velocity, but won't be lofted as high as small ones. Albini's model (1979) calculates the height to which a particle is lofted as the height where the duration of the buoyant flow structure of torching tree t_f equals the time required for the particle to travel upward from its source t_t (Finney, 2004). In order to compute the lofting height of particles with defined diameter and characteristics, some assumptions are used (Finney, 2004):

a) particles are assumed to originate at the top of the canopy;

b) flame base is assumed equal to half the stand height;

c) particles are cylinders with constant specific gravity and drag coefficient;

d) particles are lofted vertically above the burning tree.

The particles begin descending through the wind field: it is assumed that wind speed has only a horizontal component and increases logarithmically from the reference velocity provided as a simulation input (at height of 6.1 m above the vegetation). Since particle loses density and volume during burning, it descends at a decreasing rate. The user needs to set an ignition frequency, because many embers that drop on ground are not able to originate new fires. Several elements influence the ignition frequency: the most important are fuel heterogeneity, fuel moisture content, fuel temperature and other physical and thermal fuel properties (Blackmarr, 1972; Bunting and Wright, 1974; Bradshaw et al., 1984).

In order to simulate the fuel combustion, linked with smoldering and flaming fire activity behind the main flaming front, FARSITE uses the *"Burn Up" model* (Albini and Reinhardt, 1995; Albini et al., 1995). With this model the combustion history of the fuel complex, the heat flux, the gaseous emissions, the soil heating, can be simulated (Finney et al., 2003). The fuel complex is defined for each size class by woody fuel load (kg m^{-2}), heat content (kJ kg^{-1}), fuel density (kg m^{-3}), moisture content (%). The model requires as input the initial fire conditions that ignite the fuel complex, namely fire intensity (kW m^{-2}) and residence time (sec); the environmental conditions are also required, including wind speed and moisture contents of woody fuels and duff. Other information required for the Burn Up model are duff and woody fuel load. The outputs from Burn Up model are intensity (kW m^{-2}) and fuel weight loss at each timestep (kg m^{-2} min^{-1}).

Fire acceleration is defined as the rate of increase in spread rate for a given ignition source assuming all fire environmental conditions remain constant. In a strict sense, fire spread rate increases in these situations because the environmental conditions are changing to create higher potential levels of fire spread rate equilibrium (Finney, 2004). FARSITE uses a *model for fire acceleration*; this model is useful because it is able to eliminate instantaneous jumps to faster spread rates that would follow sudden increases in wind speed, steeper slopes, or changes to faster fuel types. The formula for the fire acceleration model has been proposed by Canadian Forest Fire Behaviour Prediction System, and it assumes that the fire spread rate R_t at time t is dependent on only the time allowed for accelerating to the maximum rate possible under current conditions (Forestry Canada Fire Danger Group, 1992; McAlpine and Wakimoto, 1991).

11. FARSITE Applications

FARSITE can be used for many practical applications. Finney and Andrews (1999) state that FARSITE has three main uses: simulation of past fires, simulation of active fires and simulation of potential fires. The capabilities of FARSITE are important because the fire behaviour models currently incorporated in the simulator can calculate surface and crown fire behaviour, spot fires, fire acceleration, post frontal combustion and fuel moisture (Finney, 2004).

The main potential applications of FARSITE simulator are described in the following points.

a) *Simulation of Past Fires*. FARSITE is able to simulate propagation and behaviour of past wildfires. Analyses of past fires reveal how well the simulation reproduces known fire growth patterns, given available input data. Simulating past fires is critical in developing confidence for using FARSITE to project the growth of active fires (Finney and Andrews, 1999). In order to obtain a good result, all the inputs required for the simulation have to be as similar as possible to the environmental conditions of the case studies. By considering that topography is a static parameter, the main problems are linked with the definition of the fuelbed characteristics and the rebuilding of the weather conditions.

The outputs produced by FARSITE can be very useful in order to study the fire behaviour and to evaluate if the suppression operations have been efficient and correct. The maps of fire growth and behaviour obtained with FARSITE simulations have formats suitable for Arc Map and Arc View. Since FARSITE is able to take into consideration all ground (direct, indirect and parallel) and aerial attacks, or the barrier creation, an evaluation of the global suppression intervention (with eventual mistakes or effectiveness) of the Firefighter service can be conducted.

b) *Simulation of Active Fires*. FARSITE can be used to produce simulations in order to evaluate in real time the potential propagation and behaviour of wildfires. For this aim, all the input layers indispensable to obtain a simulation must be ready for use: therefore, this application can be helpful in areas of important naturalistic interest, or in proximity of highly populated areas.

c) *Simulation of Potential Fires*. FARSITE can become an interesting tool in order to define and to manage prescribed fires. Really, FARSITE was originally intended to use it as management support tool for active prescribed fires in national parks or wilderness areas under management (Finney, 1994).

Finney and Andrews (1999) state that fire planning is an appropriate use of FARSITE and it is currently its most common application. In a given landscape, FARSITE can be used to determine the best ignition points depending on meteorological conditions, or to define when meteorological conditions and fuel status can support in the right way the fire spread. This application can be very useful in order to optimize the ratio cost of prescribed burning to effectiveness of burning. FARSITE can also be used to examine the economic consequences of potential wildfires occurring with and without fuel management activities.

With FARSITE it is possible to evaluate the efficiency of the fire propagation barriers in the landscape. Clearly, some of these barriers are natural, but other barriers can be created by Firefighters to improve the fire extinction operations.

Another interesting application of FARSITE can be represented by the creation of some extreme meteorological scenarios, with the consequent effects on fuel moisture state. For example, in Sardinia, some simulations can be produced by considering two typical extreme conditions historically tied to the most dangerous wildfires: the sirocco (dry hot south-eastern wind) windy and hot days, and the mistral (dry cold north-western wind) windy and cold days.

In areas of naturalistic interest, the creation of probabilistic maps of fire propagation and behaviour can be very useful. These maps can be produced with the use of some possible climatic and vegetational (load, moisture, etc.) scenarios.

12. FARSITE Limitations

Any fire predictive model generates estimates of fire spread and behaviour that can be affected by some inaccuracies, in both the estimated burned area extension and the values of the fire behaviour parameters (rate of spread, fireline intensity, etc.). One of the main sources of inaccuracies is linked to the difficulties in the acquisition of reliable input data, with the required spatial and temporal resolution. There are other reasons why a model may produce unreliable results. Sometimes the model is not applicable to some sites or specific situations, due to the lack of an adequate model calibration phase.

In any case, due to the complexity of the involved phenomena, the main preliminary assumptions and limitations of FARSITE simulator are following described.

1) As many simulators, the fire growth simulations of FARSITE generally get worse with time and spread distance, because there is a cumulative effect of errors. The simulation of the fire growth increases its accuracy when accurate data at high spatial and temporal resolution are used.

2) The landscape file used for the simulation is created by using different information (slope, elevation, etc.), normally with large spatial scales when the territory is wide. This simplification may worsen the accuracy of simulations at local scale, because the landscape can be too coarse to consider the environmental variability.

3) Another limitation of the fire simulator is linked with the use of simplified weather and, eventually, wind data. With respect to the first limit, actually only few studies give useful information. Finney (2004), for example, states that calculations depending on fuel temperature and moisture may not be accurate where shadows are cast by topography, precipitations vary spatially or with elevation, or water availability is significantly altered (e.g. higher fuel moistures near streams).

The limited account for topographic variations that affect wind exposure to surface fires, such as ridgetop versus sideslope versus valley (Finney, 1998; Albini and Baughmann, 1979), is another limitation of the model. For this reason, an overestimation of downslope fire perimeter and of other fire behaviour elements can be produced.

4) The scale of the used wind data (for time and space) is commonly an hour or half an hour scale, therefore it can be too coarse to consider the great variability of

wind speed and direction in the fire environment. This could force the average fire spread rate over large areas and long time to be overestimated. The fluctuations in wind directions can also overestimate the spread in the heading fire direction front, because the real fire shape has a lesser eccentricity with respect to the theoretical elliptical shape.

High frequency variability in wind direction and intensity is a common cause of non steady behaviour of fires; in these conditions many simulators produce results not consistent with observed fire propagation.

5) The interaction of multiple fire fronts observed in extreme fire conditions is difficult to model by fire simulation systems. These severe scenarios involve rapid transitions in fire behaviour, abrupt thresholds in fire activity, and strong feedbacks between fire behaviour and environmental conditions. Therefore, most models are poorly suited to explain or predict the fire behaviour in these extreme situations.

6) As already pointed out, the model of Rothermel is able to reproduce only a surface fire, spreading along a fuelbed that is continuous, uniform, homogenous, and contiguous to the ground. The fire behaviour outputs reflect a surface burning front, moving in an entirely uniform (horizontally and vertically) fuel complex, within 2 m of the ground. Clearly, this is a wide simplification of the actual surface vegetation, above all when the landscape is covered by shrublands, as it can be observed in Mediterranean areas.

7) It is not completely confirmed whether Huygens' principle is able to simulate the fire spread on complex landscapes. Some studies gave promising results, but it is important to consider that many potential sources of error in observed data (fuel maps, weather and wind data, etc.) can preclude a correct comparison between simulated and real fire.

The simple approach to correct the spread rates, too simplistic (maybe) for complex landscapes, is to assign rate of spread adjustment factors to each fuel type (Rothermel and Rinehart, 1983). These factors must be based on empirical observations of previous fires, or of phases of growth of existing fire, in patches of homogeneous fuels. They should be based on the heading portion of fire, given that spread in other directions is dependent on the elliptical dimensions. The adjustment factors, however, may not be constant throughout the duration of a fire (Finney, 2004).

8) The oval shape of the fire front perimeter observed in simplistic scenarios has been considered by many researchers to have the special configuration of an

ellipse. But some studies evidenced that there are parameter ranges for which the fire front is not even roughly elliptical, despite high regularity of fuel distribution, virtual flatness of terrain, and constancy of the wind magnitude and direction (Fendell and Wolff, 2001).

9) The most important result of FARSITE tests to be quoted has been that spread rates for all fuel models tended to be over predicted by Rothermel's spread equation (Rothermel, 1972). Sanderlin and Sunderson (1975) made a similar observation and ascribed the causes to problems relating wind speed to elliptical dimensions. Some problems may be a result of inaccurate data on fuel moistures, fuel descriptions (e.g. models), and weather. Also, wind reduction factors for forested areas and lee-side topographic sheltering can undoubtedly cause errors for spread rate calculations on some parts of a landscape (Finney, 2004).

OBJECTIVES

When FARSITE was applied in Mediterranean climate areas, results were controversial. This can be mainly attributed to the characteristics of shrubland vegetation across the Mediterranean Basin. Unlike other vegetation types, live fuel is the main component of the available fuel for fires in Mediterranean shrubland. Shrubland vegetation is usually more flammable than other vegetation types because of the low moisture content and volatile organic compounds. In addition, Mediterranean shrublands can sustain high intensity fires also within few days after rainfall and when meteorological conditions are relatively moderate. Moreover, most fire events in the Mediterranean Basin are short in duration and occur in complex-terrain areas, where spatial variability of wind speed and direction is usually wide. Realistic predictions of fire behaviour using FARSITE depend on the consistency and accuracy of the weather input data and on the accuracy of the fuel model and of the other additional parameters required by the simulator.

The main aims of this study are (1) to evaluate the capabilities of FARSITE simulator in accurately modelling the fire spread and behaviour on historical fires that burned Mediterranean maquis, and (2) to analyze the effects of fuel models, weather conditions, and topography on the simulations.

MATERIALS AND METHODS

13. Case Studies

FARSITE was used to simulate behaviour and spread of four human-caused wildland fires occurred in the western Mediterranean Basin area, in North Sardinia (Figure 31; Figure 32), during 2003, 2004 and 2006 summer season. These fires burned areas mainly covered by the typical shrubland Mediterranean vegetation, named maquis.

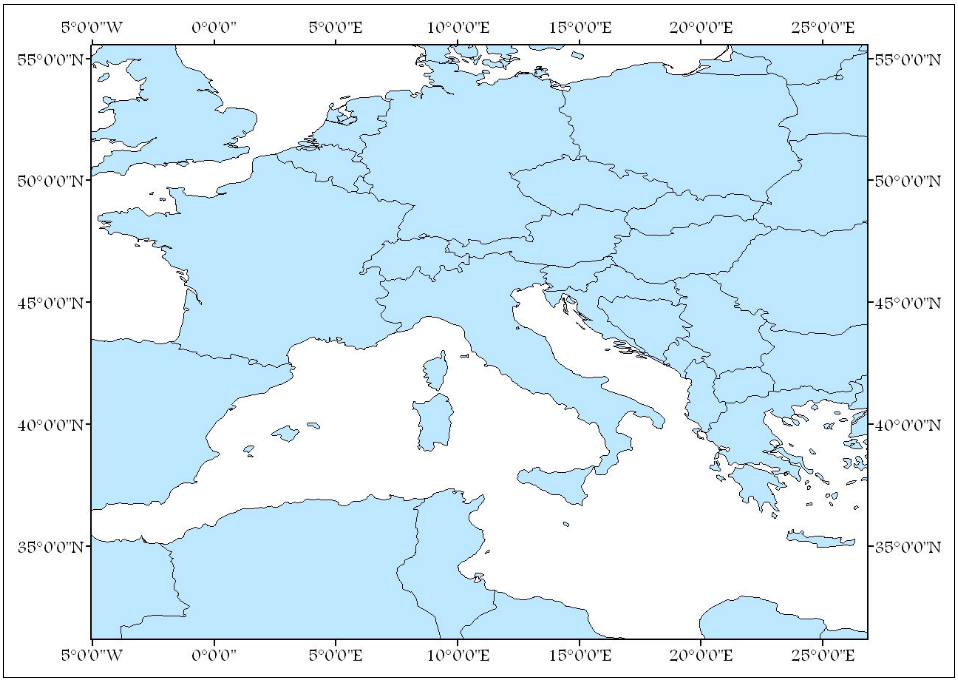

Figure 31. Geographical map of the western Mediterranean Basin

All of the case study sites, located near the coast of Sardinia, show similar climate and vegetational characteristics.

The climate is sub arid with a remarkable water deficit from May until September, and most annual rainfall amounts (approximately 700 mm, Figure 33) occur in fall and winter. During the summer season, the cumulative amounts of precipitations is instead very limited (Figure 34). The mean annual temperature along the coast line is approximately 18 °C (Figure 35), with peaks higher than 30 °C in summer season (Figure 36).

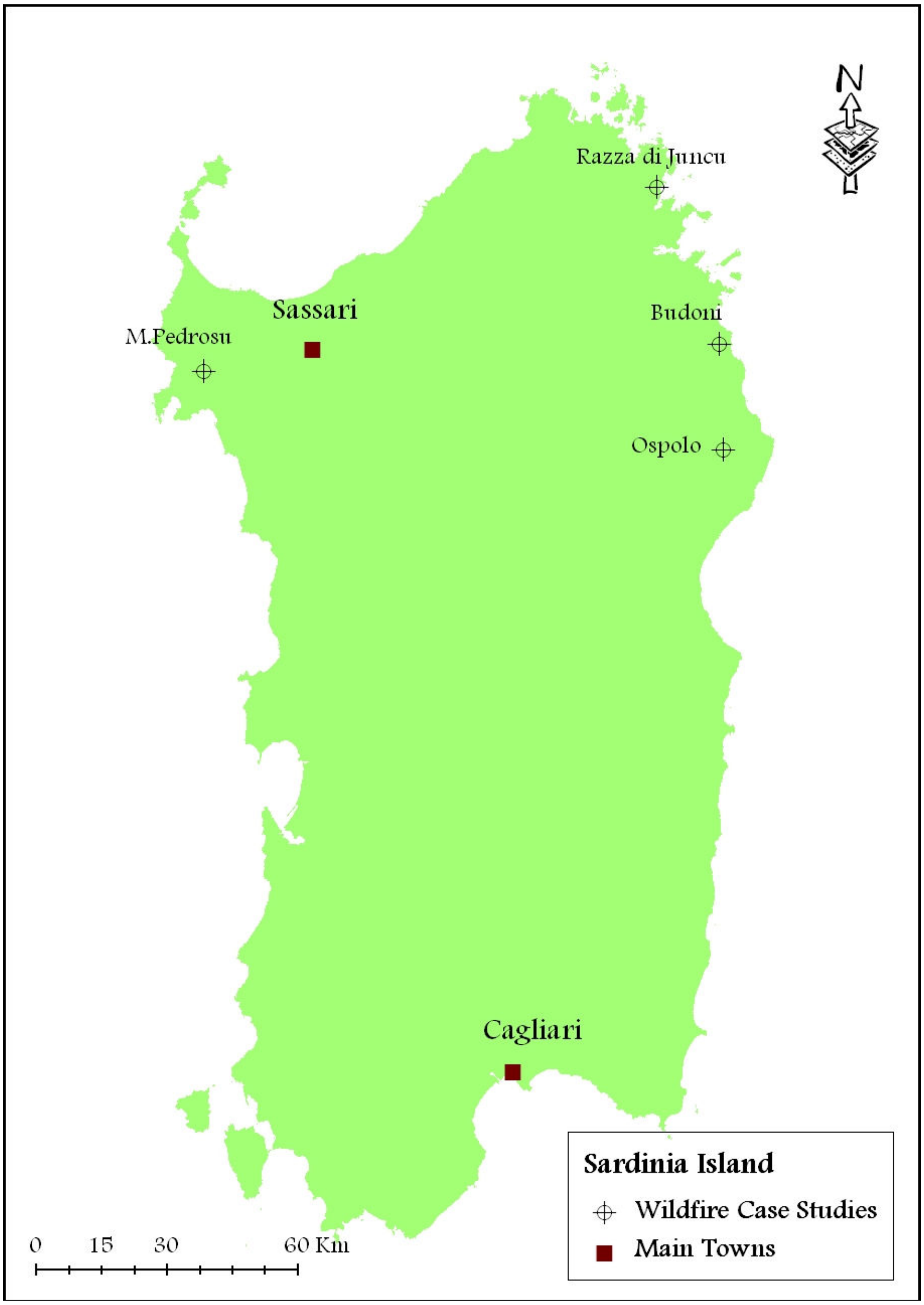

Figure 32. Sardinia map, with main towns and wildfire case studies

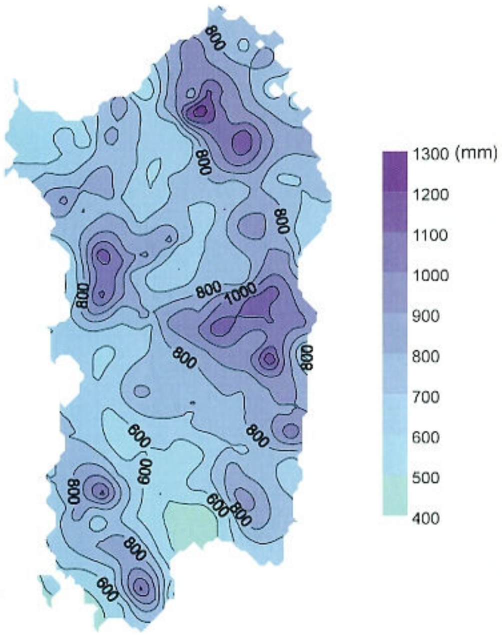

Figure 33. Sardinian annual cumulative amounts of precipitations (Chessa and Delitala, 1997)

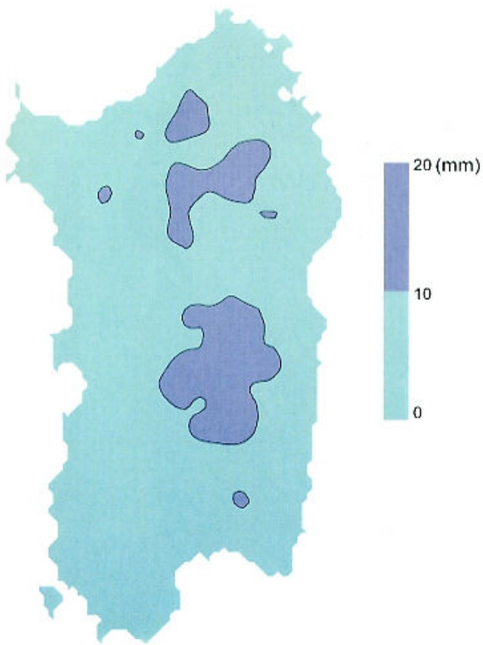

Figure 34. Sardinian cumulative amount of precipitations (in July) (Chessa and Delitala, 1997)

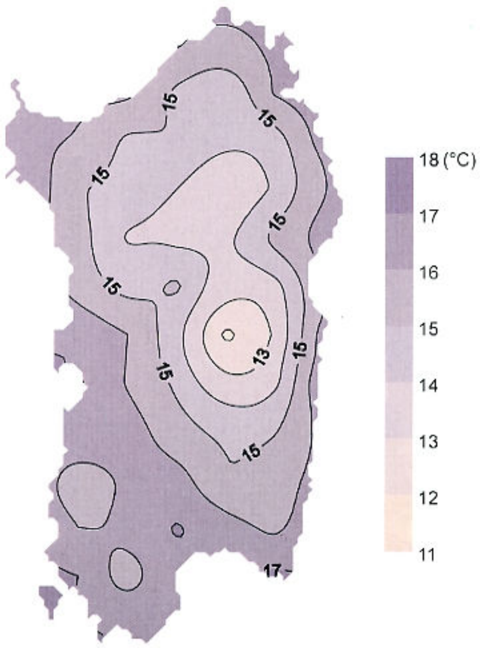

Figure 35. Sardinian mean annual temperatures (Chessa and Delitala, 1997)

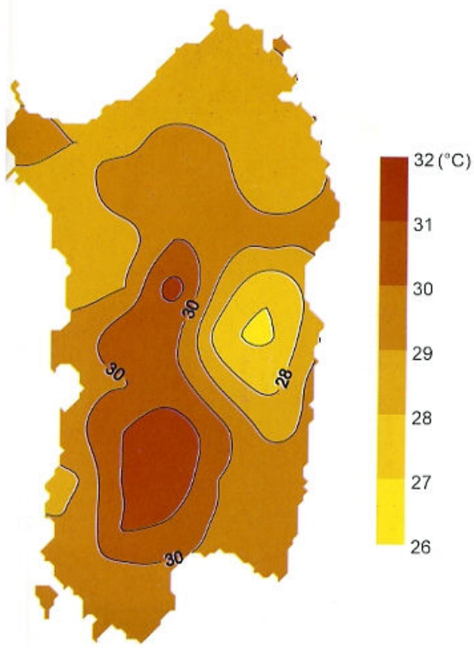

Figure 36. Sardinian mean maximum temperatures (in August) (Chessa and Delitala, 1997)

The average wind speed is relatively high (≈ 4 m s^{-1}) in both winter and summer seasons, with about 50-70% of the days showing values between 1.6 and 8 m s^{-1} (Chessa and Delitala, 1997). The prevailing wind directions at the sites are typically west and north-west with a cumulative frequency greater than 50%, as frequently observed in different Sardinian weather stations (Figure 37). However, the local wind direction, mainly with low wind intensities, can be modified by the complex terrain.

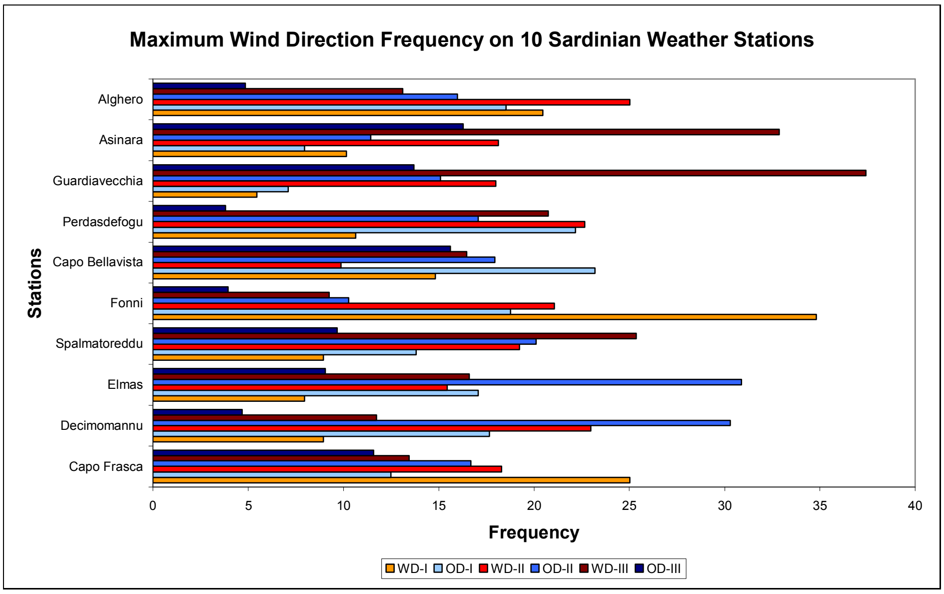

Figure 37. The maximum wind direction frequency on 10 Sardinian Weather Stations (adapted from Chessa and Delitala, 1997). The maximum wind is the observed maximum wind speed, with the associated direction, during the day

WD = western directions (225-315°); OD = other directions.

I = wind speed range 1,5-8 m s^{-1}; II = wind speed range 8-13,5 m s^{-1}; wind speed higher than 13,5 m s^{-1}

The different sites were characterized by small differences in the maquis species composition and fuel load, while great differences affected fire behaviour, fire severity and effectiveness of Sardinian Forest Service activity.

13.1. Budoni Case Study

Figure 38. Budoni three-dimensional map (source: http://www.sardegna3d.it)

This fire occurred in a hilly area near the village of Budoni, Gallura district (lat. 40° 43’, long. 09° 42’, 100 m a.s.l.) (Figure 38), on August 26, 2004, where about 145 ha were burnt. As presented in Figure 39, the area is highly populated, with many houses threatened. Because of this anthropic influence, the place presents many roads (main and secondary), that helped the direct attack near the residential areas.

The burned area (Figure 40) was mainly covered by the typical shrubland Mediterranean vegetation (approximately 104 ha), with plant height ranging from 1 to 4 m. Dominant species included *Pistacia lentiscus* L., *Olea europaea* L. *var. oleaster*, *Myrtus communis* L., *Cistus monspeliensis* L., *Calycotome spinosa* L., *Euphorbia dendroides* L. Link, *Pyrus amygdaliformis* Vill.. Small surfaces inside the area were covered by open wooded pastures and grasslands with an extension of about 22 ha and 19 ha, respectively.

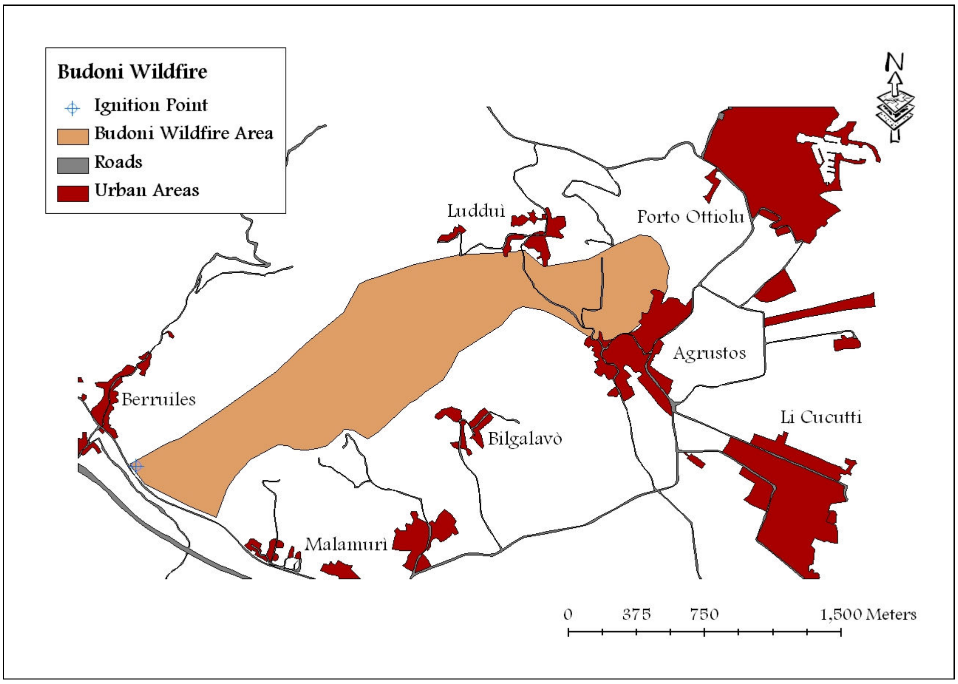

Figure 39. Budoni fire map, with roads and urban areas

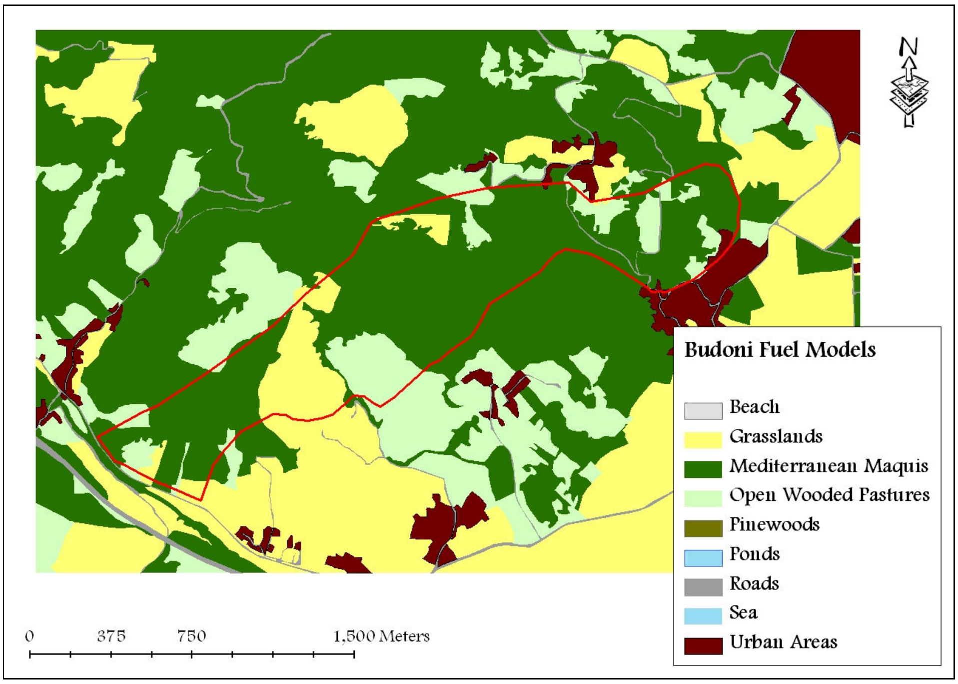

Figure 40. Budoni vegetation map; the fire perimeter is shown in red

The fire started at 5:00 p.m. LST (local solar time) near a road along the south-western side of the area. The day of the fire was very windy, but with moderate temperatures: the maximum temperature was 28 °C and was reached at 12.00 a.m. LST, the minimum was 20 °C at 9.00 p.m. LST.

The fire spreads quickly, moving towards the east driven by a strong western-south-western wind of about 35 km h^{-1} in average. The fire was successfully extinguished by Forest Service Firefighters only on the initial portion of the south flank, near the grassland area. On the opposite flank, near a ridge-line, the wind effect was reduced by the slope of terrain and the fire stopped propagating (Figure 41). The steep terrain and the strong upslope wind did not allow the direct suppression attack on the head of fire, which was slowed down only by some aerial attacks. Consequently, the spread rate of the fire front decreased significantly only after 9:00 p.m. LST, probably due to both down-slope wind flow and decreasing wind speed. However, the fire threatened some residential and resort areas on the south-east boundary. Approximately, the fire stopped its propagation at 11.30 p.m. LST, in the north-eastern border of the fire perimeter, at 1 km from sea, between Agrustos and Ludduì. The fire spread duration was 6 hours and 30 minutes.

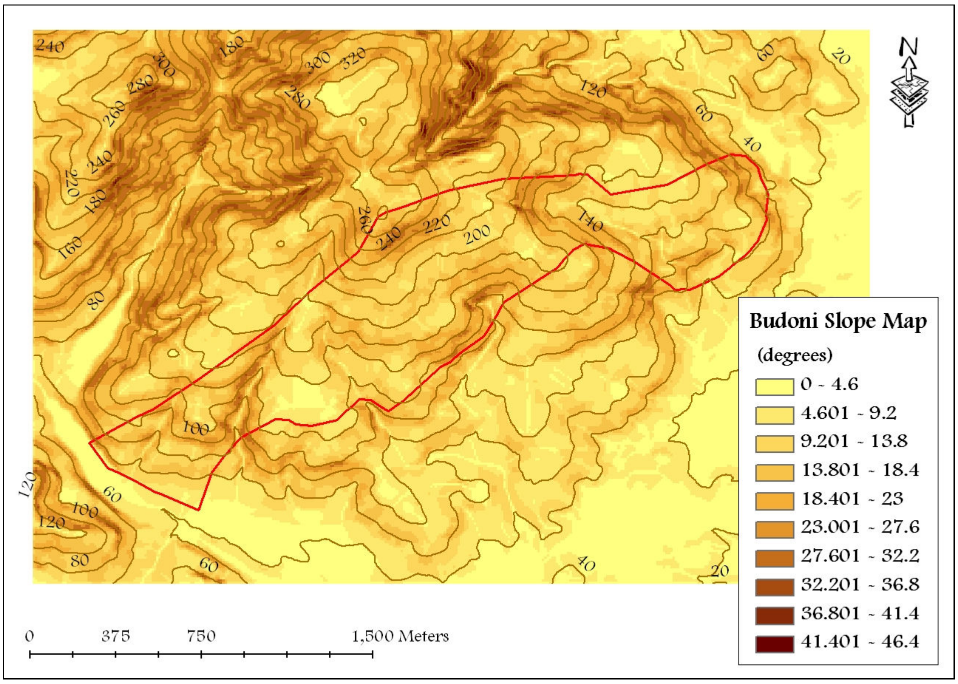

Figure 41. Budoni slope map, with isohypses of elevation; the fire perimeter is shown in red

13.2. Ospolo Case Study

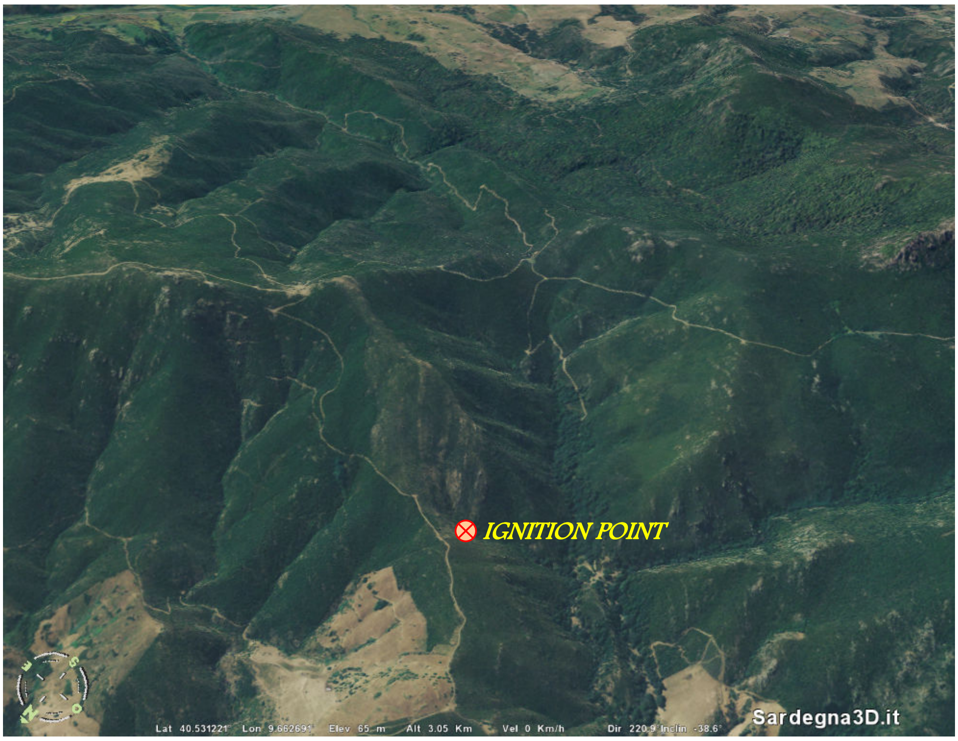

Figure 42. Ospolo three-dimensional map (source: http://www.sardegna3d.it)

The second fire occurred near the village of Siniscola, Baronia district (lat. 40° 30', long. 09° 41', 360 m a.s.l., Ospolo site), on August 21, 2004, and burned an area of about 19 ha (23 km south of Budoni fire event) covered by a mixed, dense shrubland vegetation (Figure 42 and Figure 43) with homogeneous structural characteristics and mainly composed of *Arbutus unedo* L., *Erica arborea* L., *Myrtus communis* L., *Cistus* spp., *Olea europaea* L. *var. oleaster*, *Pistacia lentiscus* L., *Phyllirea angustifolia* L..

The fire started at 7:00 p.m. LST and lasted approximately 5 hours and 30 minutes. The ignition point was located near a road along the western boundary of the area (Figure 42 and Figure 43). Although the fire event occurred in late afternoon, the weather was relatively severe, with air temperature around 24 °C and relative humidity around 35%. The fire moved towards south-east driven by a western-north-western wind (280 °), that reached an average intensity of about 15 km h^{-1} in the first two hours after ignition, till 9.00 p.m. LST. The slope helped the spread of fire towards north-west (Figure 42 and Figure 44). The fire was successfully controlled by Forest

Service Firefighters only along a road on the north flank. On the opposite flank and on the head of the fire, the steep terrain and the lack of roads did not allow a direct suppression attack (Figure 44).

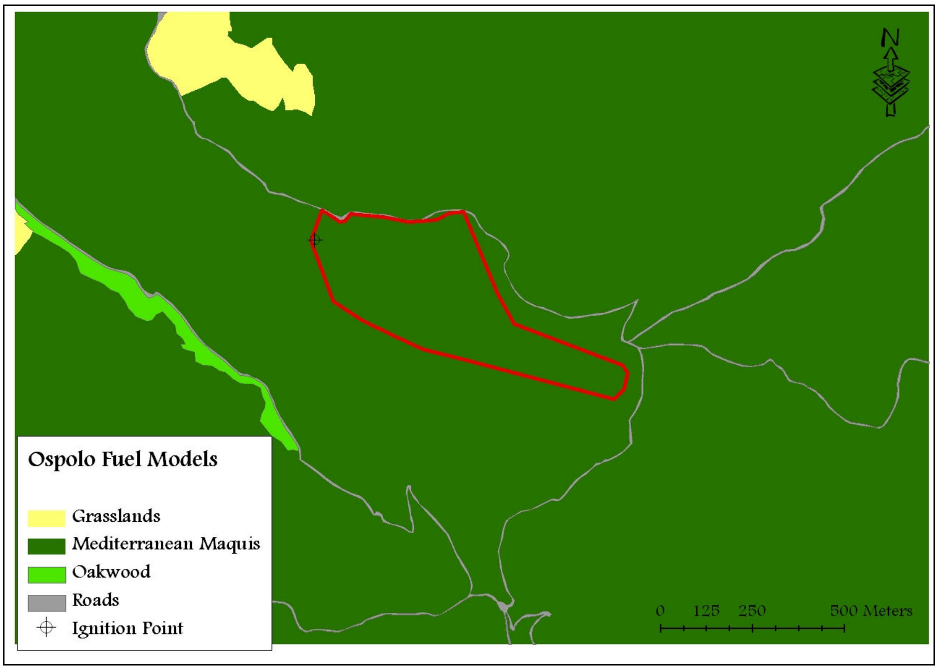

Figure 43. Ospolo vegetation map; the fire perimeter is shown in red

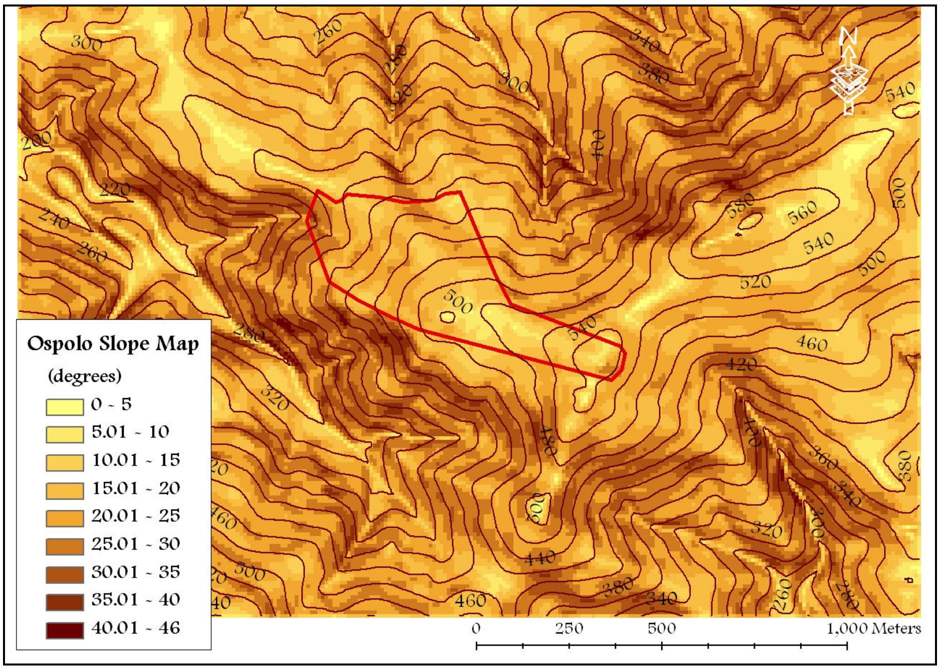

Figure 44. Ospolo slope map, with isohypses of elevation; the fire perimeter is shown in red

The spread of fire decreased near the east ridge-line, due to the effect of decreasing slope and the decrease of wind speed after 9.00 p.m. LST. Approximately, the fire stopped its propagation at 0.30 a.m. LST, after 5 hours 30 minutes of spread, in the south-eastern border of the fire perimeter, near the top of Ospolo hill, at an elevation of about 550 m a.s.l.. By considering a line between the ignition point and the farther point of the fire perimeter, Ospolo fire spreads for 930 m approximately, with a difference in elevation of about 220 m.

13.3. Razza di Juncu Case Study

Figure 45. Razza di Juncu three-dimensional map (source: http://www.sardegna3d.it)

The fire occurred at 13 km north from the village of Porto Rotondo (lat. 41° 01’, long. 09° 32’, 0 m a.s.l.), at Razza di Juncu site (38 km north of Budoni wildfire). This area, located in Gallura district, is characterized by a smooth topography, with some hills near the coast line (Figure 45 and Figure 46).

Razza di Juncu wildfire threatened the resort of Portisco and the nearby beaches; 100 people at least were saved by using some coastguard patrol boats, because there was no other chance to avoid flames. The fire burned some vehicles along the road to Razza di Juncu beach. The ignition point was located 100 meters along the helicopter base of Costa Smeralda Consortium, which was surrounded and threatened by fire.

Razza di Juncu fire occurred on August 11, 2003, and the burned area was about 45 ha. The day was characterized by a moderate western-north-western wind and was very hot: the maximum temperature recorded in the closest SAR meteorological station (39 °C) was reached at 2.00 p.m. LST, the minimum (25 °C) was reached at 6.00 p.m. LST. The vegetation type burned was a dense and uniform maquis shrubland (Figure 47), with plant height ranging from 1,5-2 m. Dominant species included *Pistacia lentiscus* L., *Cistus monspeliensis* L., *Arbutus unedo* L., *Olea europaea* L. var. *oleaster*, *Myrtus communis* L., *Pyrus amygdaliformis* Vill., *Calycotome spinosa* L., *Phyllirea angustifolia* L., *Juniperus phoenicea* L..

The fire started approximately at 12.45 a.m. LST, and the ignition point was located near the road along the north-western border of the fire perimeter. The fire moved towards south-east driven by the wind (295 °), with an average intensity of about 13 km h^{-1} till the end of fire spread.

Sardinian Forest Firefighter Service extinguished the fire with success near the road, in northern and western flanks. The direct attack in the maquis zone was not possible, because the fire arrived at the beach very soon. Afterwards, the fire propagated mainly towards the south direction, with a limited effect of wind and slope. Some attaches were conducted along the south flank, using helicopters (Helitanker) and an airplane (Canadair). Razza di Juncu wildfire had an important rate of spread till the fire arrived at the sea, then its velocity of propagation reduced. The fire stopped its spread approximately at 3.45 p.m. LST, after about 3 hours.

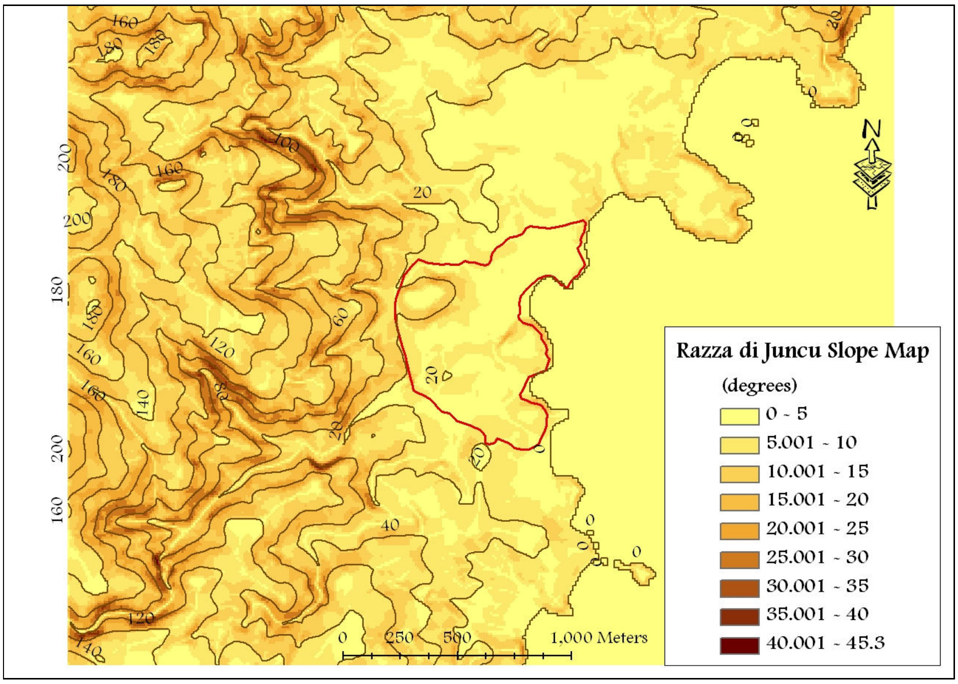

Figure 46. Razza di Juncu slope map, with isohypses of elevation; the fire perimeter is shown in red

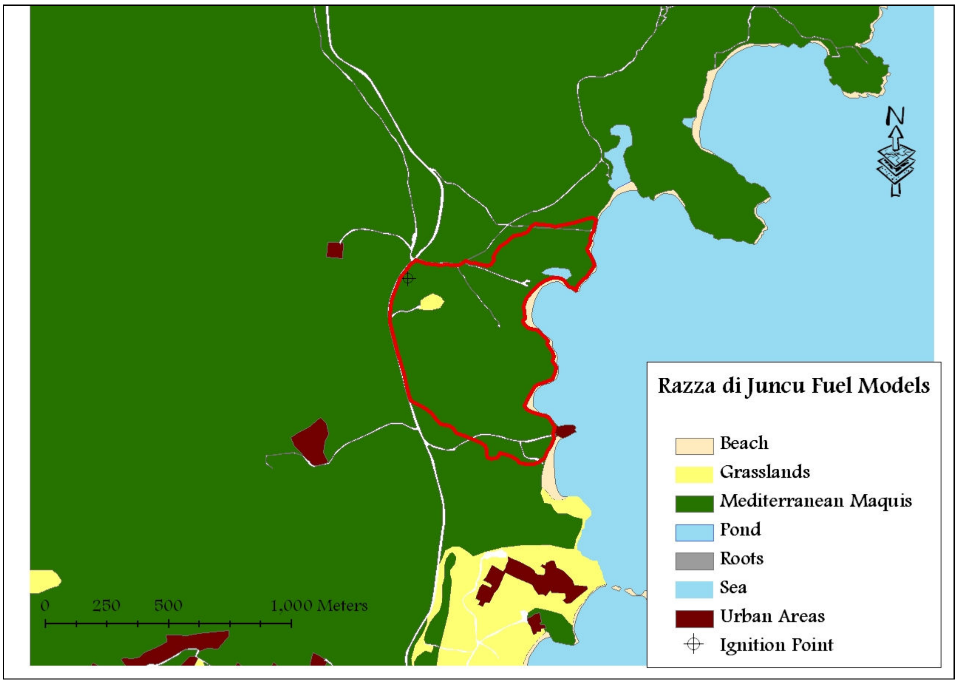

Figure 47. Razza di Juncu vegetation map; the fire perimeter is shown in red

13.4. Monte Pedrosu Case Study

Figure 48. Monte Pedrosu three-dimensional map (source: http://www.sardegna3d.it)

Monte Pedrosu wildfire occurred 13 km to the north of the town of Alghero (lat. 40° 33', long. 08° 18', 0 m a.s.l.), in July 2006. This site is located in Nurra district, in a flat area characterized by a smooth topography, with only small hills with an elevation of about 200 m a.s.l, partially burned by this fire (Figure 48 and Figure 49).

The area was subjected to recurrent arson fires in the last years, principally during severe environmental conditions in such a way to permit the fire spread towards the peaks of the hill. Monte Pedrosu wildfire affected the eastern part of the hill. The fire threatened some rural houses and the village of Santa Maria La Palma; due to the presence of houses and of agricultural lands, the viability in this area is good.

Monte Pedrosu wildfire occurred on July 15, 2006, at 2.30 p.m. LST; the burned area was about 65 ha. The day was characterized by a light wind, with some occasional gusts, but it was very hot: the maximum temperature recorded in the closest meteorological station was 36 °C and it was reached at 3.00 p.m. LST, the minimum was 20 °C at 7.00 a.m. LST. The vegetation type burned was mainly maquis (about

87% of the total burned area) (Figure 50), with plant height ranging from 1-1,5 m. Dominant species included *Pistacia lentiscus* L., *Myrtus communis* L., *Chamaerops humilis* L., and some *Arbutus unedo* L.. The maquis was not so uniform and it was denser at the bottom of the hill. The remaining vegetation was grassland, concentrated near the road, especially in the zone nearby the ignition point.

The ignition point was located near the road along the north-eastern boundary of the area. The fire moved towards south-west driven by mild slope and by north-eastern wind (40 °), that reached an average intensity of about 11 km h^{-1} till 7.00 p.m. LST, then it decreased. Sardinian Forest Firefighter Service extinguished the fire with good success near the road. The direct attack in the maquis zone was not easy, because of the heat released by fire. So, in that central region, the fire attack was mainly carried out by aerial forces. When Monte Pedrosu wildfire overtook the hilly chain, the rate of spread decreased, also because of downwind; then, after 7.00 p.m. LST, also the wind speed reduced, so the fire propagation became slower. The fire stopped its spread approximately at 7.45 p.m. LST, after about 5 hours and 15 minutes.

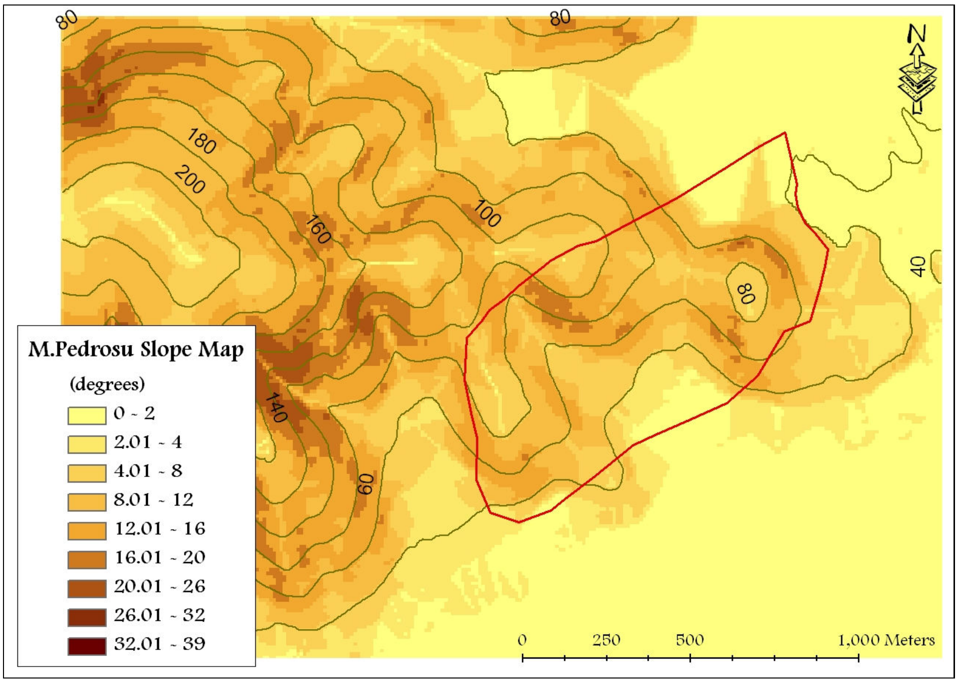

Figure 49. Monte Pedrosu slope map, with isohypses of elevation; the fire perimeter is shown in red

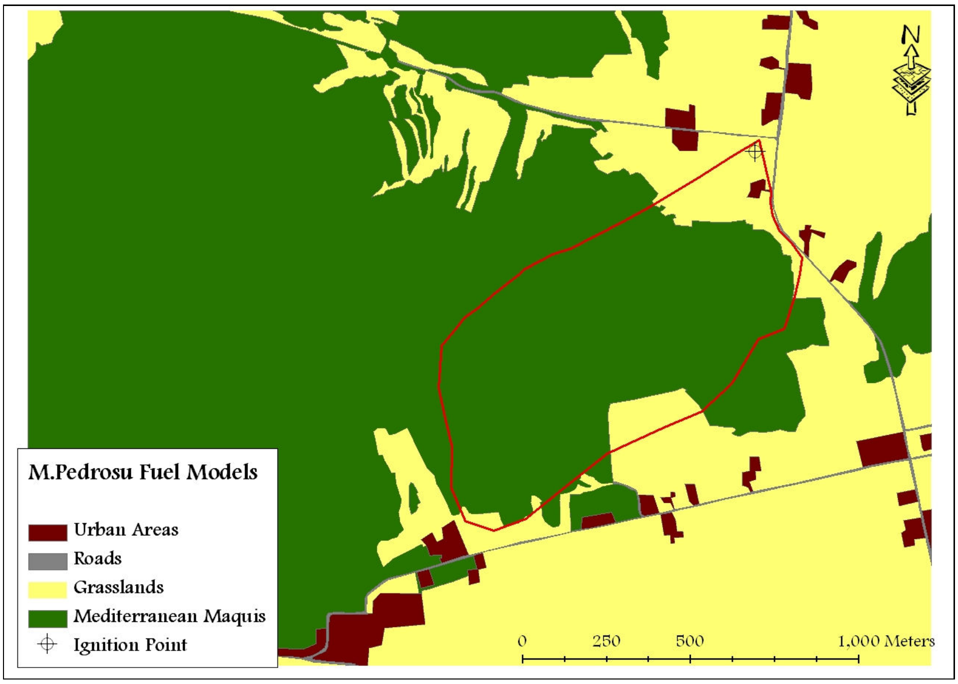

Figure 50. Monte Pedrosu vegetation map; the fire perimeter is shown in red

14. FARSITE Simulation Parameters

As it discussed before, FARSITE simulator requires a set of spatial data, referred to topography, vegetation and meteorological conditions. In addition, a set of simulation parameters must be defined.

All the input layers required to run FARSITE simulator have been acquired and managed by using a Geographic Information System GIS (ArcGis 9, ESRI Inc., Redlands, CA, USA). The grid resolution for the spatial information of layers has been defined by considering the extension of burned areas and of surrounding landscape: a grid resolution of 10 m was used for Ospolo and Razza di Juncu fires, while a grid resolution of 15 m was used for Monte Pedrosu and Budoni. All the raster themes were converted into raster ASCII format, in order to support the definition of the landscape file into FARSITE simulator.

The Digital Elevation Model (DEM) and the elevation map of each area were derived from the Carta Tecnica Regionale of Sardinia by using the Triangular Irregular Network (TIN) algorithm. The additional themes of slope and aspect were derived from DEM using the Spatial Analyst tool of ArcGIS 9.

Fuel model and canopy cover maps were produced by supervised classifications of pre-fire aerial photographs (1 : 10,000) and by field observations of plant community; some parts of landscapes were mapped using CORINE land cover map (1 : 25,000) of Sardinia (EEA, 2002). In the first steps polygons were drawn onto the pre-fire aerial photographs, and afterwards these polygons were ground-truthed, corrected where necessary and allocated to fuel model and canopy classes.

The fuel model map gives a fuel model code for each point of the grid. For each fuel model code the values of the following physical characteristics must be provided by an ASCII file:

- fuel load;
- SAV ratio;
- depth of surface fuelbed;
- moisture of extinction;
- fuel heat content.

In all the case studies, the vegetation was mainly composed of shrubland vegetation, and partially of grassland and wooded pasture.

To describe the shrubland vegetation characteristics, standard fuel models of Anderson (1982) (model n° 4, FM4) and Scott and Burgan (2005) (models 142, SH2;

145, SH5; 147, SH7) were used. With Anderson's FM4, "*fire intensity and fast-spreading fires involve the foliage and live and dead fine woody material in the crowns of a nearly continuous secondary overstory. Stands of mature shrubs, 6 or more feet*[*] *tall, such as California mixed chaparral, the high pocosin along the east coast, the pinebarrens of New Jersey, or the closed jack pine stands of the north-central States are typical candidates. Besides flammable foliage, dead woody material in the stands significantly contributes to the fire intensity. Height of stands qualifying for this model depends on local conditions. A deep litter layer may also hamper suppression efforts*" (Anderson, 1982). In Scott-Burgan's SH2, "*the primary carrier of fire is woody shrubs and shrub litter. Moderate fuel load, depth about 1 foot (about 33 cm), no grass fuel present. Spread rate is low; flame length low*" (Scott and Burgan, 2005). In Scott-Burgan's SH5, "*the primary carrier of fire is woody shrubs and shrub litter. Heavy shrub load, depth 4-6 feet (about 130-200 cm). Spread rate very high; flame length very high. Moisture of extinction is high*" (Scott and Burgan, 2005). In Scott-Burgan's SH7, "*the primary carrier of fire is woody shrubs and shrub litter. Very heavy shrub load, depth 4 to 6 feet. Spread rate lower than SH5, but flame length similar. Spread rate is high; flame length very high*" (Scott and Burgan, 2005).

In order to account for the site specific characteristics of shrubland vegetation (Figure 52), a custom fuel model was developed and tested. This fuel model, named Custom Model Maquis 28 (CM28), was realized using field sampling data from recent and former studies conducted in North Sardinia and bibliographic information on the Mediterranean Basin, on similar types of vegetation (Leone et al., 1993; Fernandes, 2001; Baeza et al., 2002; Caria, 2003; Pellizzaro et al., 2003, 2005; De Luis et al., 2004; Cruz, 2005). Field data were collected from destructive sampling conducted in North Sardinia, in 2 m x 2 m plots located in maquis areas. This destructive sampling has been conducted in different sites, with similar shrubland characteristics, located in Gallura district (Monti, lat. 40° 48', long. 09° 20') and in the northern part of Nurra district (Porto Palmas, lat. 40° 74', long. 08° 15'; Monteforte, lat. 40° 74', long. 08° 19').

Vegetation of any plot was weighted, distinguishing dead and live fuel and, for dead fuel, the 1 hr, 10 hr, 100 hr timelag size classes. For live fuel and for each timelag size class some samples were prepared (Figure 51). All samples were afterwards dried in oven at 102 °C for 96 h, in the CNR-IBIMET labs of Sassari, in

[*] 1 foot is equal approximately to 0.33 meters

order to evaluate the dry weight and to calculate the fuel moisture content for any category.

Figure 51. Samples of live and dead fuel, divided in timelag size classes, before the ovendry at 102 °C

To determine the SAV ratio for dead and live fuel, in any plot some twigs and leaves were considered as representative of the shrubland vegetation; for the selected twigs and leaves, the SAV ratio values were recorded. For each plot, the fuelbed depth and the specific shrubland composition were determined. In order to evaluate the moisture of extinction, a value reported by many studies as typical for the Mediterranean maquis was used. The standard value proposed by Anderson (1982), Pyne et al. (1996) and Scott and Burgan (2005) was used for the fuel heat content.

The main difference between shrubland standard fuel models and CM28 is primarily due to the fuel load characteristics: the latter have a higher ratio live/dead fuel load.

Figure 52. Variability in fuel species, load, height and complexity in eight different areas covered by Mediterranean maquis.

A previous custom fuel model (CM20) for the Mediterranean shrubland vegetation was defined by Caria (2003), for a maquis study area located in north-western Sardinia, in Capo Caccia peninsula (lat. 40° 36', long. 08° 09', 150 m a.s.l.). This custom fuel model is useful for Capo Caccia local vegetation, but it is unfit for the maquis vegetation of the four case studies, located in different places and with some shrub species and fuelbed height differences. Actually, Arrigoni (1968) defined Capo Caccia vegetation as "brush and coastal maquis of southern and middle-eastern Sardinia, and partially of Nurra planes (north-western Sardinia)". In any case, also the CM20 confirms that the ratio live/dead fuel load is greater than one, unlike the main shrubland fuel models (Anderson, 1982; Scott and Burgan, 2005).

Grasslands and wooded pastures were assigned to Anderson standard fuel models n° 1 (FM1) and n° 2 (FM2) respectively (Anderson, 1982). With Anderson's FM1, "*the fire spread is governed by the fine, very porous, and continuous herbaceous fuels that have cured or are nearly cured. Fires are surface fires that move rapidly through the cured grass and associated material. Very little shrub or timber is present, generally less than one third of the area. Grasslands and savanna are represented along with stubble, grass-tundra, and grass-shrub combinations that met the above area constraint. Annual and perennial grasses are included in this fuel model*" (Anderson, 1982). With Anderson's FM2, "*the fire spread is primarily through the fine herbaceous fuels, either curing or dead. These are surface fires where the herbaceous material, in addition to litter and deaddown stemwood from the open shrub or timber overstory, contributes to the fire intensity. Open shrub lands and pine stands or scrub oak stands that cover one-third to two-thirds of the area may generally fit this model; such stands may include clumps of fuels that generate higher intensities and that may produce firebrands*" (Anderson, 1982).

Scott and Burgan non-burnable fuel model n° 91 (NB1) (Scott and Burgan, 2005) was used for urban and suburban areas and for roads.

Table 7 resumes the characteristics of the fuel models used for the case study simulations.

Each <u>canopy cover layer</u> was created from the fuel model maps by the addition of a field to the attribute table, defining the canopy cover percentage. The canopy cover layers in all case studies have been created by considering no tree presence in the maquis vegetation. So, in the shrubland zone the canopy cover was set as zero. The grid files were created using the canopy cover field value as raster cell value; afterwards, the grid files were converted into ASCII format.

Table 7. Characteristics of the fuel models used in the simulations

Fuel mode code	***FM1 (AND.)***	***FM2 (AND.)***	***FM4 (AND.)***	***SH2 (S.&B.)***	***SH5 (S.&B.)***	***SH7 (S.&B.)***	***CM28***	***CM20***
	Grassland	*Open Wooded Pasture*	*Shrub*	*Shrub*	*Shrub*	*Shrub*	*Shrub*	*Shrub*
Fuel Model Parameters								
- Dead Fuel Load (Mg ha^{-1})	1.66	7.84	24.70	10.09	12.78	24.66	9.86	5.46
1-hr	1.66	4.48	11.23	3.03	8.07	7.85	3.92	4.75
10-hr	0	2.24	8.99	5.38	4.71	11.88	3.92	0.71
100-hr	0	1.12	4.48	1.68	0	4.93	2.02	0
- Live Fuel Load (Mg ha^{-1})	0	1.12	11.23	6.50	6.50	7.62	17.93	6.35
Herbaceous	0	0	0	0	0	0	0	0
Woody	0	1.12	11.23	8.63	6.50	7.62	17.93	6.35
Fuel Model Type	static	static	static	static	static	static	static	static
- Dead 1-hr SAV (cm^{-1})	114	98	65	24	24	24	60	62
- Live Herbaceous SAV (cm^{-1})	0	0	0	0	0	0	0	0
- Live Woody SAV (cm^{-1})	49	49	49	52	52	52	50	82
- Fuelbed Depth (cm)	30.48	30.48	182.88	30.48	182.88	182.88	200	35
- Moisture of Ext. (%)	11	14	20	14	14	14	25	25
Dead Heat Cont. (kJ kg^{-1})	18620	18620	18620	18620	18620	18620	18620	20934
Live Heat Cont. (kJ kg^{-1})	18620	18620	18620	18620	18620	18620	18620	20934
Fuel Moisture (%)								
- Dead (%)								
1-hr	5	5	8	8	8	8	8	5
10-hr	8	8	11	11	11	11	11	8
100-hr	12	12	13	13	13	13	13	12
- Live (%)								
Herbaceous	0	0	0	0	0	0	0	0
Woody	0	100	60	60	60	60	60	76
Adjustment	1.0	1.0	1.0	1.0	1.0	1.0	1.0	

Since the vegetation of wildfire case study areas can be considered like a surface layer, with maximum height of 3-4 m only for some isolated big shrub in

Budoni wildfire, the tree canopy characteristics (crown base, height, bulk density, foliar moisture content, diameter, species, and shade tolerance) were not considered.

So, all FARSITE simulations reproduced a surface fire spreading in the surface layer of shrub, wooded pastures and grasslands of the landscapes. Therefore, in these fuel conditions, crown fire or spot fire were not simulated with FARSITE.

Sometimes also maquis can experience spot fire phenomena, and therefore the choice to avoid spot fire in FARSITE simulations can be considered as simplistic. At the moment, we don't have adequate data and information about incidence and characteristics of the spot fire phenomenon in Mediterranean shrublands. The choice to consider only a surface fire spread, with no spot fire phenomena, was also linked with the low accuracy of FARSITE spot fire model: in literature there are few case studies in which the spot fire module has been used, and there are no sufficient validations of this module.

The *fuel moisture* information was determined by integrating field observations and some literature data.

Shrubland and grassland live fuel moisture content was determined by drying several samples in oven.

In order to determine the actual dead fuel moisture content for the different case studies, the values for 10 hr timelag class were estimated calculating the relationship between fuel moisture content (direct measurements) and fuel moisture sensor (model CS505, Campbell Sci., Logan, UT, USA) in days with meteorological conditions similar to those when the fire events occurred. The 1 hr and 100 hr timelag dead fuel moisture content values were obtained from field observations and literature data (for shrubland vegetation, Fernandez, 2001; Baeza et al., 2002; De Luis et al., 2004).

FARSITE considers as constant in space and time the value of live fuel moisture, whereas dead fuel moisture can change. For this reason, in the simulations of the wildfire case studies a conditioning period of two days (before the fire day) was considered.

In order to rebuild *meteorological conditions* of the wildfire days, hourly meteorological data (air temperature, relative humidity, wind speed and direction, solar radiation, rainfall) were obtained from the closest weather stations of Sardinian Agrometeorological Service (SAR) network. The relative shortwave radiation (i.e., ratio between solar and extraterrestrial radiation) was used to define cloud cover conditions (Colliver, 1991), a parameter required to define the FARSITE weather file. Since the relative shortwave radiation was always above the 0.60 threshold, the cloud cover value was assumed equal to 0 throughout the day (Aubinet, 1994).

Meteorological data were input as hourly values for wind speed and direction and for cloud cover, whereas rainfall, maximum and minimum temperature and maximum and minimum relative humidity were input as daily data. For temperature values, FARSITE requires also the hour in which minimum and maximum were recorded.

The *weather file* was created for each simulation to represent temperature, humidity, and precipitation amount for the area over the fire period. All meteorological information was provided as ASCII format data stream.

The *wind data* inserted in FARSITE are required at 6.1 m above the top of the vegetation. For all the wildfire case studies, many FARSITE simulations were done using wind field maps in raster format to determine the effect of wind field data on the accuracy of simulations.

For this purpose, for all the case studies the model NUATMOS (Ross et al., 1988) was used to obtain some numerical simulations of the wind field over complex terrain, and to evaluate the effect of topography on wind regime and on fire spread (Figure 53).

NUATMOS produces a 3D mass consistent wind field based on observations arbitrarily located (Carvalho et al., 1997), and satisfies the equation of continuity. The NUATMOS input data required for the wind field rebuilding are wind speed and direction at a given number of punctual locations. For all NUATMOS simulations, the wind data of SAR weather station network closest to the fire events were used.

NUATMOS is a mass conservative model, but it doesn't solve the problem of momentum conservation; due to its linear character, the non linear phenomena associated with the flow over steeper topography cannot be predicted. In effect, NUATMOS is a model quite realistic to simulate wind fields in smooth topography landscapes (Lopes, 2003): for this reason the NUATMOS simulations are not so realistic for the event of Budoni.

Therefore, in order to simulate the behaviour of Budoni wildfire with FARSITE, additional wind speed and direction data were collected using a portable instrument (mod. MPM2000, Solomat Corp., Stamford, CT, USA) at different locations across the burned area to simulate the effect of topography (ridge-top, side slope and valley bottom) on prevailing wind regime during the event. The wind maps were interpolated using the Inverse Distance Weighted method as incorporated into ArcGis 9.1 (Watson and Philip, 1985).

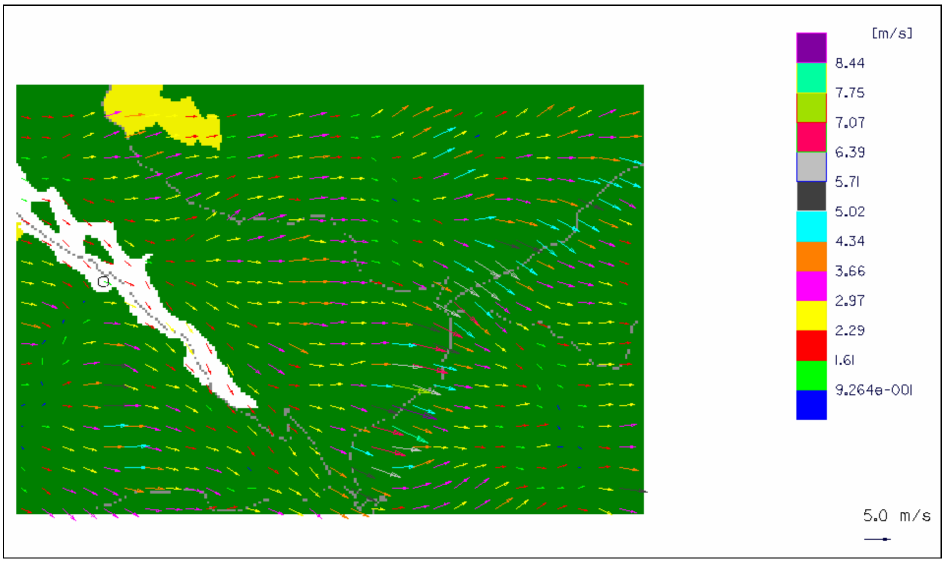

Figure 53. Example of NUATMOS simulation for the wind field map production

For all simulations, the *adjustment factor* for fire rate of spread was set at 1.0 for all fuel models.

All the simulation *outputs* obtained by FARSITE have been exported and managed by using a GIS.

For each simulation the fire perimeter shapefile and the eight raster outputs have been exported, in order to understand and to describe fire behaviour and dangerousness.

Raster outputs produced by FARSITE for the fire behaviour characteristics have ASCII format, and their resolutions have been set between 10 and 30 m, by considering the dimension of the case study boxes.

15. Statistical Analysis of FARSITE Simulations

Several simulations were conducted to compare the performance of FARSITE simulator when different combinations of fuel models and input parameters (mainly, wind field) were used.

The output parameters provided by FARSITE were the fire perimeter for each timestep, the time of arrival of fire for each point of grid, the rate of spread. Each output was exported in vector or raster format.

The final surface fire area obtained by FARSITE simulation and the actual fire area, in vector format, were transformed into raster format and reclassified as burned and unburned areas, by considering a rectangular box in relation with the whole extension of each wildfire case study. The same procedure was applied on the partial burned areas, by dividing simulated and actual fire areas in partial perimeters, at defined timesteps.

The observed fire area grid, classified in burned and unburned categories, was converted to text file, and later was imported as table of points (with X and Y coordinates, and the associated values) in the GIS project. Therefore, the box containing the observed fire area can be defined as a set of sample points with two possible values: burned and unburned.

The union between the observed fire perimeter and the simulated perimeter permits to obtain four possible cases, which are defined a, b, c, d in Figure 54.

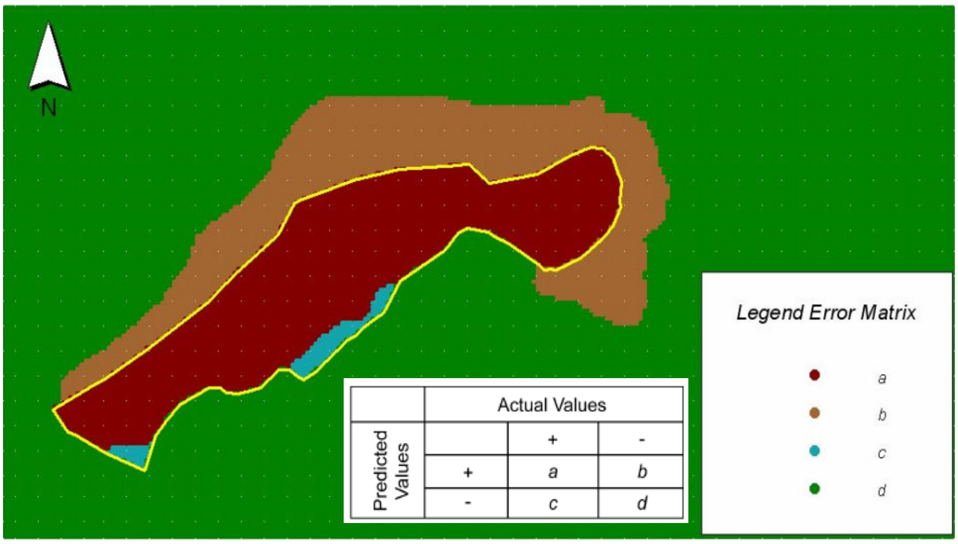

Figure 54. The union between observed and simulated fire perimeter, with the four possible cases and the error matrix

Commento: Descrivere meglio questa nuova figura

In Figure 54, b defines the false positive points, c defines the false negative, a and d the correct estimation respectively for burned and unburned areas.

An error matrix between actual and simulated fire areas was calculated to define the frequency of each case (presence/absence of burned areas). If we consider presence or absence of fire, the error matrix is represented by a square matrix: the diagonal elements are the number of cases where observed and simulated fire areas agree, whereas the off-diagonal cells contain the numbers of misclassified items.

The accuracy of each simulation was evaluated using two statistical indicators of binary association between burned and unburned areas, derived from the error matrix: Cohen's kappa coefficient (Congalton, 1991; Congalton and Green, 1999) and Sørensen's coefficient (Legendre and Legendre, 1998).

Cohen's kappa coefficient (K) is a standard nonparametric measure of the classification accuracy, which allows the evaluation of the overall agreement between two sets of categorizations (simulated and actual areas) while correcting for chance agreements between the categories (Jenness and Wynne, 2005). This statistic is especially useful for estimating the accuracy of predictive models measuring the agreement between the simulated areas of the predictive model (FARSITE) and the observed burned area. Cohen's kappa coefficient makes use of both model overall accuracy and accuracies within each category in terms of agreement between simulated and observed areas.

K values were calculated as follows (Congalton and Green, 1999):

$$K = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_{1+}x_{+1})}{N^2 - \sum_{i=1}^{r}(x_{1+}x_{+1})} \qquad (33)$$

where r is the number of rows in the matrix, x_{ii} is the number of observations in row i and column i, x_{i+} and x_{+i} are the marginal totals of row i and column i, respectively, and N is the total number of observations.

K values typically range between 0 and 1, with values closest to 1 indicating a higher agreement. When K values are equal to 0, the agreement between observed and simulated cases is only due to chance. Negative values are possible, but rare, and they indicate the complete disagreement among observations.

Since K is asymptotically normally distributed, a basic Z-score was used for significance testing. Therefore, the Z-score was used to determine the overall accuracy values exceeding those obtained from chance agreement (Congalton and Green, 1999), and the significance of the differences in K values among simulations (Congalton and Mead, 1983). The Z-score was calculated as follows:

$$Z = \frac{K_1}{\sqrt{(var\,K_1)}} \quad (34)$$

where K_1 is the K value obtained for a generic simulation n° 1, with the associated variance.

The significance of Z-score is evaluated based on the associated P-value. If the hypothesis testing is employed, the null hypothesis H_0: $K_1 = 0$ or the alternative hypothesis H_1: $K_1 \neq 0$ can be verified. The null hypothesis means the accuracy of classification is by no means different from a purely random classification. The alternative hypothesis means the accuracy of classification is significantly different from a random classification; in this case, H_0 is rejected at some critical Z-score.

Variance and K statistic can be used also to calculate an interval of confidence around K:

$$IC = K_1 \pm Z_{\alpha/2}\sqrt{var(K_1)} \quad (35)$$

For the evaluation of all case study simulations, with the use of an error matrix, a confidence interval equal to 0.95 was used.

To evaluate if different features (i.e. fuel models, fuel moisture content, etc.) or methodologies (i.e. uniform or gridded wind fields) produce significantly different results on fire perimeters, two K values can be compared (Congalton and Mead, 1983); for this purpose the Z-score is calculated as:

$$Z = \frac{|K_1 - K_2|}{\sqrt{[var(K_1) + var(K_2)]}} \quad (36)$$

where K_1 and K_2 are the K values obtained for two generic simulations n° 1 and n° 2, with the associated variances.

Considering the hypothesis testing, in this case we have to consider the hypothesis H_0: K_1-K_2 = 0, or the alternative one H_1: K_1-$K_2 \neq 0$.

Assuming a two-sided test (K_1 is different from K_2), the H_0 hypothesis will be rejected if the Z-score value is major-equal to $Z_{\alpha/2}$.

The comparison between two K values can be extended to a general test for multiple K values, by first estimating the supposed common kappa value K_c (as described by Fleiss, 1981):

$$K_c = \frac{\sum_{m=1}^{g} \frac{K_m}{var(K_m)}}{\sum_{m=1}^{g} \frac{1}{var(K_m)}} \quad (37)$$

The K_c common value obtained from the previous equation can subsequently be used in order to test for equal values on the Chi-Square distribution with *g-1* freedom degrees:

$$\chi^2_{equalK} = \sum_{m=1}^{g} \frac{(K_m - K_c)^2}{var(K_m)} \quad (38)$$

The second statistical index was Sørensen's coefficient (SC), an asymmetric index that is an indicator of the exclusive association between burned areas (both observed and simulated).

SC values were calculated as follows:

$$SC = \frac{2a}{2a + b + c} \quad (39)$$

where *a* is the number of cells coded as burned in both observed and simulated data, *b* is the number of cells coded as burned in the simulation and unburned in the actual fire, and *c* is the number of cells coded as unburned in the simulation and burned in the actual fire.

The significance of the association was determined using the frequencies from the error matrix, and calculating the Chi-square statistic to test the null hypothesis of independence between observed and simulated areas (Ludwig and Reynolds, 1988).

Moreover, the actual rate of spread (ROS) for the partial extent of the burned surfaces was estimated dividing the vector amplitude (L) from one perimeter to the next by the time (T) needed to move from the first to the second perimeter (ROS = L/T, m min $^{-1}$). ROS values for each fire event were estimated computing the sum of both L and T over the entire duration of fire and then dividing the sum of L by the sum of T.

RESULTS

16. Budoni Case Study

As mentioned in the section of materials and methods, the wildfire of Budoni involved predominantly a wildland area, but threatened some residential areas on the east flank. Most burned area was covered by maquis, and the other small surfaces by open wooded pastures and grasslands. Despite the presence of anthropic activities, the limited network of roads in some areas did not permitted an effective attack by Firefighters, while the aerial attack was limited by the meteorological conditions (strong wind), the presence of other big fires in neighbouring areas, and because the fire started in late afternoon. The fire evolved essentially unmanaged, and therefore the case study of Budoni can be considered a good test site in order to evaluate the accuracy of the fire spread and the behaviour predictions provided by FARSITE simulator.

The general description of the simulation performances for the final and partial fire perimeters of Budoni case study is reported in the next tables. Maps of simulated and actual fire behaviour and spread are shown in Figure 56 and Figure 57.

Statistical analysis showed that the best performance for Budoni wildfire was obtained using the CM28 custom fuel model for shrubland vegetation (Table 8); as already pointed out, FM1 was used to reproduce the grass areas, and FM2 for the open wooded pasture areas.

Table 8. Statistical evaluation of FARSITE performance by different simulations on the final perimeter of the fire event occurred in Budoni, Italy, on August 26, 2004. The letters a, b, c, refer to the number of cells correctly and wrongly estimated.

Simulation (Fuel Models)	SC	K	a	b	c
1° (FM1, FM2, FM4)	0.34**	0.12**AA	1592	6044	10
2° (FM1, FM2, SH5)	0.38**	0.17**BB	1592	5192	10
3° (FM1, FM2, SH7)	0.45**	0.28**CC	1592	3834	9
4° (FM1, FM2, CM28)	0.72**	0.65**DD	1579	1212	23

SC, Sørensen's coefficient; K, Cohen's kappa coefficient;

* $P \leq 0.05$; ** $P \leq 0.01$; SC values followed by ** indicate a significant association between burned and unburned areas at $P \leq 0.01$ by χ^2 test; values of K followed by the same letters are not significantly different at $P \leq 0.05$ (one letter) or at $P \leq 0.01$ (two letters) by Z-score test

a, burned area agreement; b, overestimated area; c, underestimated area

Cohen's kappa coefficient (K) was used to measure the overall agreement between simulated and actual burned and not burned areas, after that the chance agreement was removed from the analysis (Congalton, 1991). K values show that all simulations estimated the spatial extension of burned and unburned areas better than the random chance at $P \leq 0.01$. The best value of K coefficient (Table 8) was obtained by the simulation n° 4 (K = 0.65), whereas the other simulations (standard fuel models FM4, SH5, and SH7) gave K values ranging from 0.12 and 0.28. Comparing the standard fuel models, the higher K values were obtained using the SH7 fuel model (simulation n° 3), with K values of 0.28. The worst performance was provided by the FM4 fuel model (simulation n° 1), with K value of 0.12, due to a systematic overestimation of the actual burned area. A comparison of the K values obtained from the different simulations was done using the Z-test. Results showed that all the differences among the simulations were significant at $P \leq 0.01$ (Table 8).

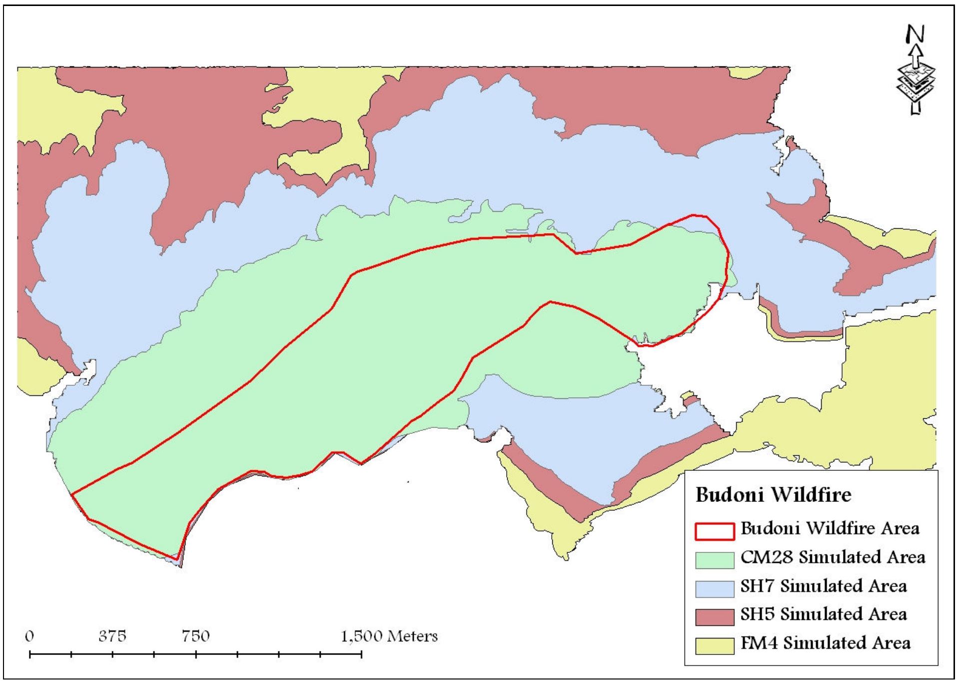

Figure 55. Comparison between observed and simulated fire areas using different fuel models for the fire event occurred in Budoni

Since Sørensen's coefficient (SC) is an asymmetric index, it is an indicator of the exclusive association among burned areas (actual and simulated). Once more, the best agreement among areas (Table 8) was obtained by the simulation n° 4 (SC = 0.72), while the other simulation runs showed values less than 0.45. The lowest

SC values were obtained by simulations n° 1 and 2, when the fuel models FM4 (simulation n °1) and SH5 (simulation n° 2) were used (SC values respectively equal to 0.34 and 0.38).

The wide overestimation of the burned areas (Table 8) obtained by the standard fuel models generally determined poor performances that can be explained by the inadequacy of some fuel model parameters in describing the characteristics of the maquis vegetation, in particular in terms of load and SAV ratio.

The performance of the simulation n° 4 was evaluated using SC coefficient on three different partial steps (i.e., on three different burning periods) within +02:00, +03:30, and +06:30 hours from the ignition starting time. Table 9 shows the good agreement obtained between actual and simulated fire areas obtained for both the first (SC = 0.70) and the second timestep (SC = 0.81), while the third step indicated a clear decrease in the SC value (0.63).

Table 9. Values of Sørensen's coefficient (SC) obtained for simulation n° 4 by partial timesteps of the fire event occurred in Budoni. The SC value for the whole area is also shown

Step	SC
1	0.70
2	0.81
3	0.63
Whole area	0.72

The good performance obtained during the first step, when the burned area was mainly covered by shrubland vegetation (87%), was confirmed during the second burning period, although a large burned surface was covered by grasslands (24%) and open wooded pastures (17%). Therefore, the fuel models used to simulate the actual fire behaviour seem to be reasonable. During the third burning period, the accuracy of the simulation was probably reduced by the decrease in wind speed and down-slope wind conditions.

The above mentioned statistical tests showed a good accordance between actual and simulated fire areas. The essentially adequate performance of FARSITE can be probably explained by the accuracy of the custom fuel model in describing the characteristics of the shrubland vegetation of the area. However, the wind field is a key factor in determining the fire behaviour; for this reason, additional analyses were devoted to investigate the effect of the accuracy of the wind field data on FARSITE simulation.

Raster maps were realized by two different approaches: the use of a statistical method based on the spatial interpolation of the wind data (Interpolated Wind Field, IWF), and the numerical simulation by the mass-consistent NUATMOS model (MCM-WF); raster maps were realized using wind speed and direction data collected on seven points and used in order to initialize the simulations.

Table 10. Statistics obtained for three different FARSITE simulations (using CM28 with different wind field maps) on the final perimeter of the fire event occurred in Budoni, Italy, on August 26, 2004. The letters a, b, c, refer to the number of cells correctly and wrongly estimated.

Simulation (Wind Fields)	SC	K	a	b	c
IWF	0.72**	0.65**AA	1579	1212	23
MCM-WF	0.64**	0.54**BB	1593	1773	9
CWF	0.60**	0.49**CC	1590	2083	12

SC, Sørensen's coefficient; K, Cohen's kappa coefficient;

* $P \leq 0.05$; ** $P \leq 0.01$; SC values followed by ** indicate a significant association between burned and unburned areas at $P \leq 0.01$ by χ^2 test; values of K followed by the same letters are not significantly different at $P \leq 0.05$ (one letter) or at $P \leq 0.01$ (two letters) by Z-score test

a, burned area agreement; b, overestimated area; c, underestimated area

The statistical analysis (Table 10) showed that FARSITE performances were improved substituting interpolated maps of wind field (IWF, MCM-WF) for constant wind field (CWF), in order to account for the combined effect of wind field and topography on fire spread. Statistical analysis conducted on K values also showed that the three simulations obtained with different wind field maps are statistically different for $P = 0.01$ (Table 10). The use of raster maps provided by the mass consistent NUATMOS model (MCM-WF) did not furnish improvements of accuracy in comparison with the raster maps obtained by IWF method (Table 10 and Figure 55).

The different runs of simulation n° 4 realized using IWF and CWF showed similar accuracy values during the first and second timesteps (Table 11), when a strong upslope wind propagated the fire. The simulation results obtained using interpolated maps showed a better accuracy in comparison with the constant wind field during the third time step, when the complexity of the terrain greatly affected local wind conditions (Figure 56). Actually, the area burned during the third timestep is characterized by a high spatial variability in slope and elevation, with many sectors involved in the fire characterized by down slope wind conditions.

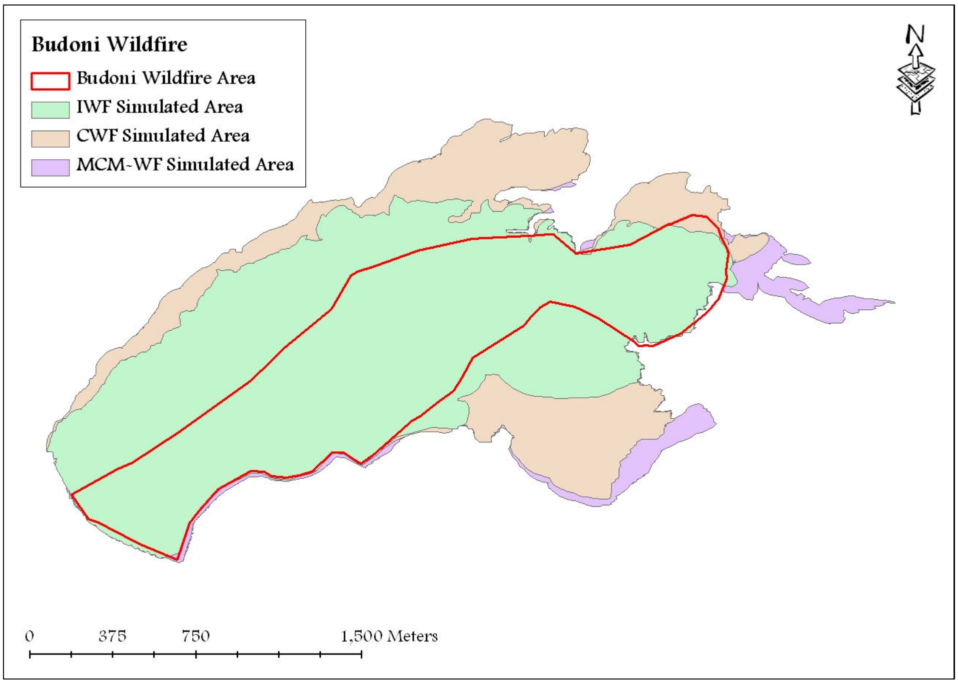

Figure 56. Comparison between observed and simulated fire areas (using CM28 custom fuel model) obtained with raster wind map (IWF), NUATMOS wind field map (MCM-WF) and constant wind field map (CWF) for the fire event occurred in Budoni

Table 11. Values of Sørensen's coefficient (SC) obtained for simulation n° 4 using raster maps of interpolated wind field (IWF) and constant wind field (CWF) for the fire event occurred in Budoni. The SC values for the whole area are also shown

Step	IWF	CWF
1	0.70	0.70
2	0.81	0.78
3	0.63	0.48
Whole area	0.72	0.60

The ROS gives general information on the effect of fuel and environmental conditions on fire behaviour. Observed ROS ranged from 7 to 12.4 m min^{-1} for the first and second steps respectively (Table 12), with a lower value (6.6 m min^{-1}) for the third burning period.

Table 12. Observed and predicted rate of spread (ROS, m min-1) obtained from simulation n° 4 for the fire event occurred in Budoni. The ROS values for the whole area are also shown

Step	Observed ROS	Simulated ROS
1	7.00	6.50
2	12.40	10.30
3	6.60	7.40
Whole area	8.10	8.10

The estimated mean values of ROS are in agreement with the actual mean value for the first and third steps, with an underestimation of about 2.1 m min^{-1} for the second step. Figure 57 shows the spatial variation of the simulated ROS.

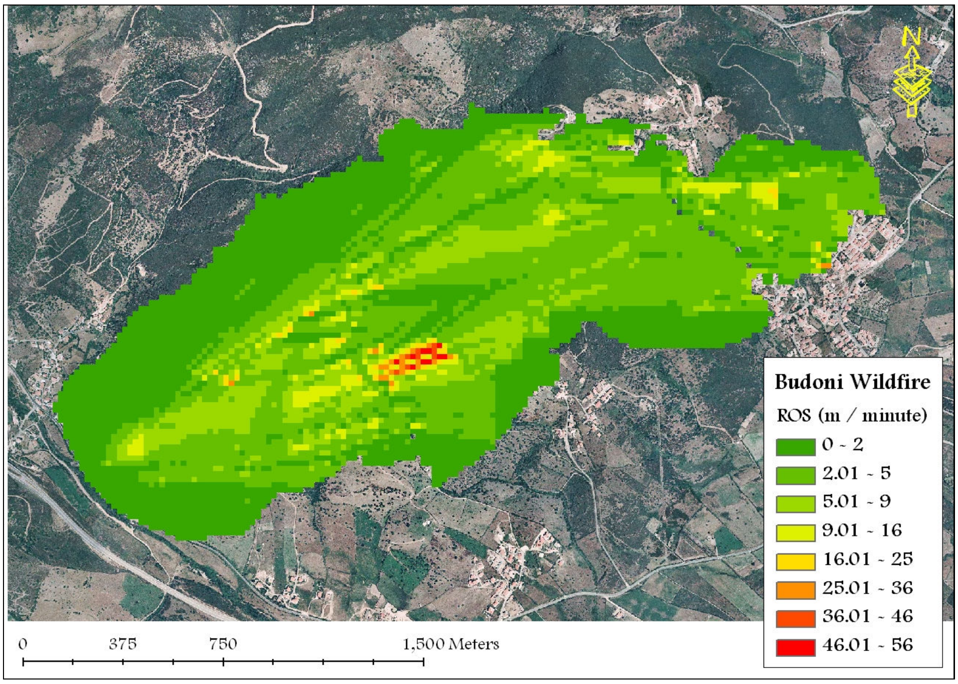

Figure 57. Rate of Spread (ROS, m min^{-1}) predicted by simulation n° 4 for the fire event occurred in Budoni

Slope, together with the canopy cover characteristics and their relative effect on wind speed, were the principal factors affecting the magnitude and the spatial variations of ROS. The maximum values of ROS (42-56 m min^{-1}) were reached during the second burning period in a small area characterized by open wood pasture vegetation. In fact, this type of vegetation was not able to remarkably reduce the strong upslope wind speed; in addition, the steepness of the terrain produced an additional effect on ROS. The lowest values of simulated ROS (< 9 m min^{-1}) were obtained across the areas covered by maquis, and intermediate values were observed when the fuel was represented by open wooded pastures and short and sparse shrubland vegetation.

17. Ospolo Case Study

The wildfire of Ospolo burned an area of about 19 ha, and involved a hilly zone completely covered by Mediterranean maquis. The vegetation can be considered basically the same potential vegetation as in Budoni case study. The area of Ospolo is actually characterized by a mixed dense shrubland vegetation with different species association (mainly *Arbutus unedo* L., *Myrtus communis* L., *Erica arborea* L.), but with mean values of both plant height and fuel load comparable with the case study of Budoni.

Despite the fire started in late evening and stopped its spread in the night, the weather was relatively severe and the fire was driven by a western wind with intensity of about 15 km h^{-1} during the first hours of the event. In addition the fire was not effectively managed by Firefighters, because most attacks were concentrated along the road, on the northern flank of the fire perimeter.

Because of the above mentioned similarities between Budoni and Ospolo, this case study can be considered an independent validation site for the CM28 custom fuel model applied on Budoni.

FARSITE simulations were realized by using a constant wind field (CWF, 15 km h^{-1} till 9.00 p.m. LST, 12 km h^{-1} after 9.00 p.m. LST) and wind maps provided by NUATMOS mass-consistent model (MCM-WF), initialized with the wind data collected by the nearest weather station of SAR network.

A wide description of the simulation performances is reported in the next tables (Table 13 and Table 14); maps of simulated and observed fire behaviour and spread are shown in Figure 58, Figure 59 and Figure 60.

The experimental results summarized in Table 13 confirmed the results provided by the CM28 custom fuel model on the case study of Budoni. All the statistical analysis showed that the FARSITE simulations with the CM28 custom fuel model are the most appropriate in order to obtain good accuracy in predictions of the fire perimeter, spread and behaviour.

In particular, the statistical tests showed that the CM28 fuel model together with constant wind field (CWF) provided a K value equal to 0.61 (SC equal to 0.63), while the other simulations conducted using standard fuel models (FM4, SH5, SH7, SH2) gave K values ranging from 0.03 and 0.45 (and SC values ranging from 0.12 and 0.46) (Table 13).

Table 13. Statistics obtained for different FARSITE simulations on the final perimeter of the fire event occurred in Ospolo, Italy, on August 26, 2004. The letters a, b, c, refer to the number of cells correctly and wrongly estimated.

Simulation (Fuel Models)	SC	K	a	b	c
FM4	0.12	0.03^{AA}	305	4535	0
SH5	0.17^{**}	0.09^{**B}	305	3032	0
SH7	0.18^{**}	0.11^{**B}	305	2720	0
SH2	0.46^{**}	0.45^{**CC}	93	4	212
CM28-CWF	0.63^{**}	0.61^{**DD}	305	352	0
CM28-MCM-WF	0.68^{**}	0.66^{**EE}	305	284	0

SC, Sørensen's coefficient; K, Cohen's kappa coefficient;

* $P \leq 0.05$; ** $P \leq 0.01$; SC values followed by ** indicate a significant association between burned and unburned areas at $P \leq 0.01$ by χ^2 test; values of K followed by the same letters are not significantly different at $P \leq 0.05$ (one letter) or at $P \leq 0.01$ (two letters) by Z-score test

a, burned area agreement; b, overestimated area; c, underestimated area

K and SC values showed that all simulations estimated the spatial extension of burned and unburned areas better than the random chance at P < 0.01, with the exception of the FM4 fuel model. Among the standard fuel models, the SH2 fuel model, with K value equal to 0.45 (SC = 0.46), furnished the best results, probably for the reason that the model is characterized by low fuel load and height and different SAV ratios with respect to the other models. FM4 fuel model provided the worst performance (K = 0.03; SC = 0.12), confirming the overestimation of burned areas observed in the case study of Budoni. A wide overestimation of the burned area is confirmed also for the SH5 and SH7 fuel models.

A clear increase of K values was obtained using MCM-WF maps; Z-test exhibits that the increases of K values were significant for P < 0.01. SC values confirmed the results, showing that the best agreement between observed and simulated burned areas (0.63-0.68) was obtained using CMM28 (Figure 58).

Figure 58 and Figure 59 show the fire areas predicted by the main simulations. The simulation obtained with CM28 and MCM-WF maps provided a simulated burned area characterized only by a small systematic overestimation on both the fire front and flanks. These results can be explained with the orographic characteristics of the burned area, that does not show high variations in slope with respect to Budoni case study, where different sections of the burned area were characterized by down-slope wind conditions.

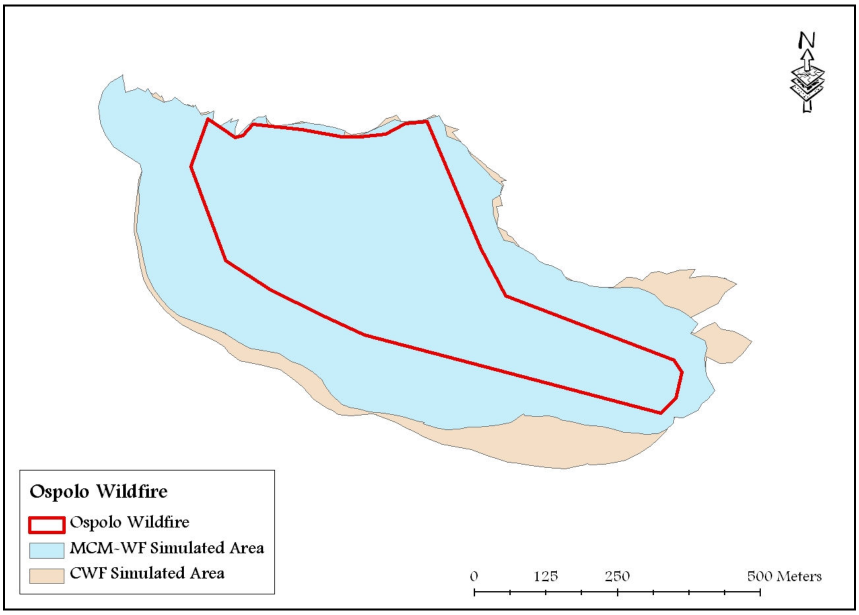

Figure 58. Comparison between observed and simulated fire areas (using CM28 custom fuel model) obtained using MCM-WF and CWF maps for the fire event occurred in Ospolo

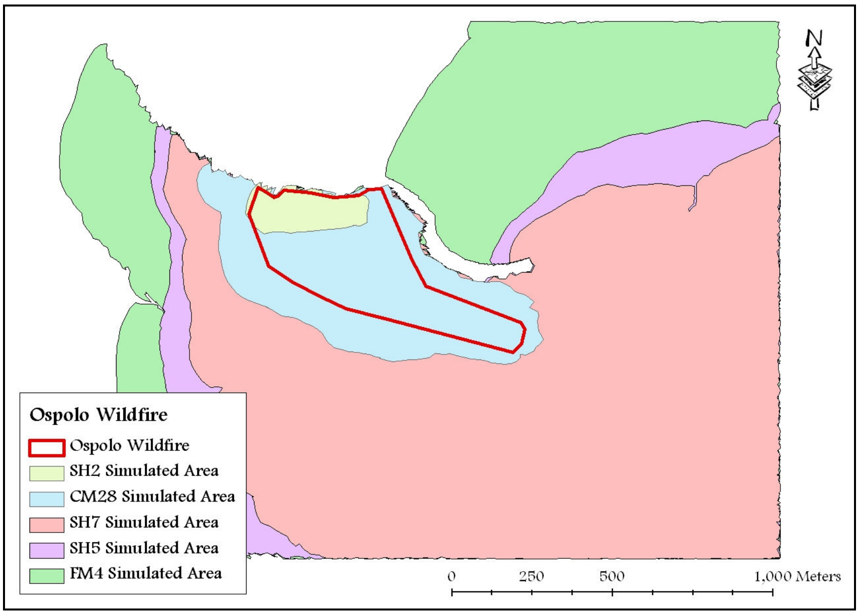

Figure 59. Comparison between observed and simulated fire areas obtained using custom and standard fuel models for Ospolo wildfire, with MCM-WF maps

The observed final rate of spread of Ospolo wildfire was about 2.8 m min^{-1} (Table 14). Again, the best performance in predicting rate of spread was obtained using the CM28 fuel model and the raster wind field map produced by NUATMOS, by which ROS value is approximately equal to 3 m min^{-1}.

Table 14. Observed and predicted average rate of spread (ROS, m min^{-1}) obtained from all the fuel models simulations, using both uniform and gridded wind field, for the fire event occurred in Ospolo

FUEL MODEL	SIMULATED ROS (m min^{-1})		OBSERVED ROS (m min^{-1})
	MCM-WF	CWF	
FM4	45.1	49.0	2.8
SH5	25.1	35.0	
SH7	21.2	23.3	
SH2	1.1	1.2	
CM28	3.0	3.1	

As shown in Figure 60, the highest values of rate of spread were reached with high values of the wind-slope vector magnitude; in these zones ROS values reached 4-5 m min^{-1}, but most simulated ROS values were under 2 m min^{-1}.

As already observed for the simulated burned area, also for the maximum rate of spread it is confirmed that some standard fuel models (SH7, SH5, FM4) strongly overestimate this parameter with respect to the observed value, in particular the FM4 fuel model (45-50 m min^{-1}) (Table 14).

On the other hand, when FARSITE simulation runs with the SH2 fuel model, a large underestimation of ROS (ranging from 1.1 and 1.2 m min^{-1}) can be observed.

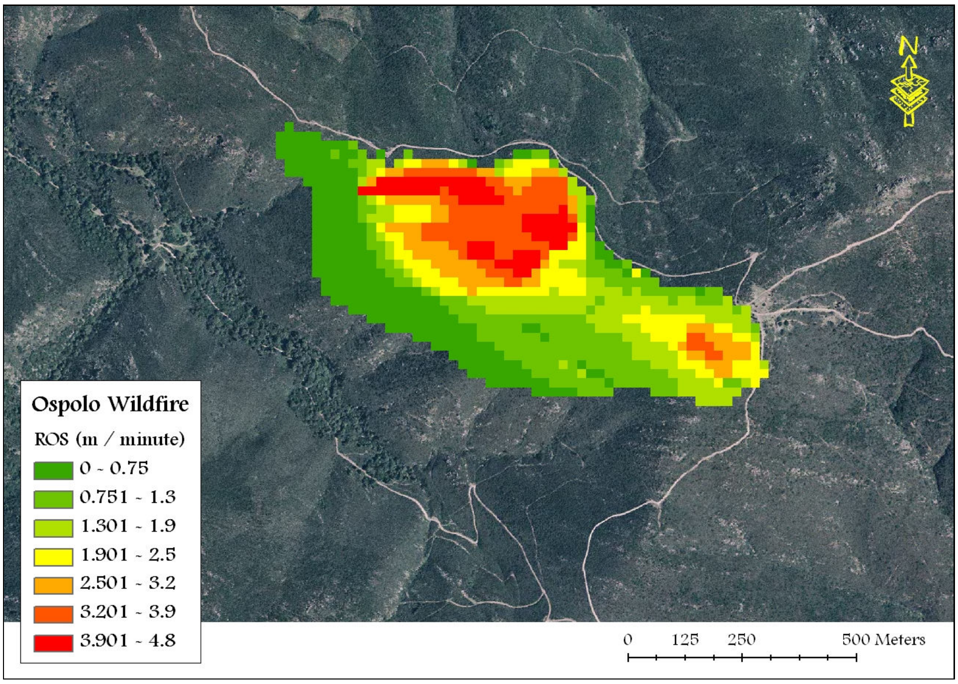

Figure 60. Rate of Spread (ROS, m min^{-1}) predicted by CM28 fuel model and MCM-WF map for the fire event occurred in Ospolo

18. Razza di Juncu Case Study

The wildfire of Razza di Juncu burned a coastal area of about 45 ha, in a flat zone covered by Mediterranean maquis. The vegetation was characterized by dense shrub formations, with species, plant height and fuel load similar to the vegetation of Budoni case study. The fire of Razza di Juncu was very characteristic, because the spreading wildfire stopped to burn on the coast line. Therefore, the shape of real fire and of all FARSITE simulations have been affected by the presence of this natural "barrier" (Figure 61).

The actual fire started at 12.45 a.m. LST. The fire spreads quickly because of the wind intensity (13 km h^{-1}) and the high temperatures of the day (39 °C). When the fire reached the coastal line, the propagation has been possible only on the flanks, so the rate of spread was very high only in the first hour of the burning period. The fire front propagated almost unmanaged during the first period, because the Firefighters concentrated their initial efforts on the evacuation of tourists from the close beaches.

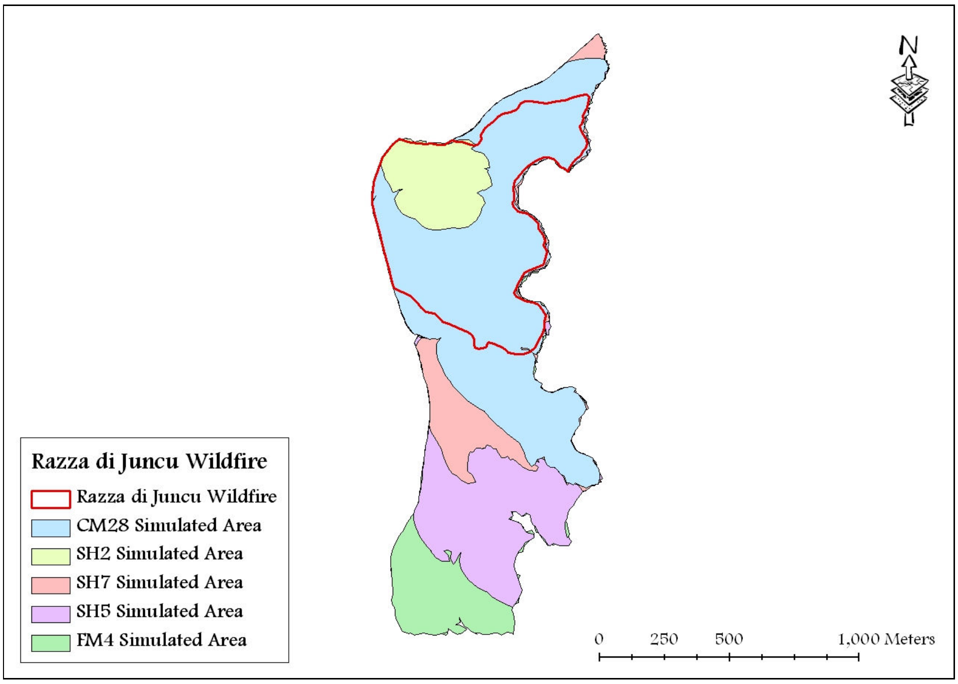

Figure 61. Comparison between observed and simulated fire areas (with NUATMOS wind field map) obtained using custom and standard fuel models for Razza di Juncu wildfire

Also for this case study, FARSITE simulations were realized by using both constant wind field (CWF, 13 km h^{-1}) and wind field maps obtained with NUATMOS model, with wind information collected by the nearest weather station of SAR network.

The performances of the FARSITE simulations are reported in Table 15 and Table 16; the maps of simulated and observed fire area, spread and behaviour are shown in the next figures.

The values of the statistical parameters reported in Table 15 confirmed the results obtained on Budoni and Ospolo case studies with the use of the CM28 fuel model. Therefore, the simulations of FARSITE with CM28 permitted to obtain high accuracies in the predictions of the burned area and of the fire spread and behaviour.

Table 15. Statistics obtained for different FARSITE simulations on the final perimeter of the fire event occurred in Razza di Juncu, Italy, on August 11, 2003. The letters a, b, c, refer to the number of cells correctly and wrongly estimated.

Simulation (Fuel Models and Wind Maps)	SC	K	a	b	c
FM4-CWF	0.57**	0.55**AA	526	783	1
FM4-MCM-WF	0.59**	0.56**AA	526	739	1
SH5-CWF	0.62**	0.59**BB	526	658	1
SH5-MCM-WF	0.62**	0.59**BB	525	648	2
SH7-CWF	0.73**	0.72**CC	526	383	1
SH7-MCM-WF	0.73**	0.72**CC	526	384	1
SH2-CWF	0.55**	0.53**D	202	11	325
SH2-MCM-WF	0.37**	0.36**E	122	3	405
CM28-CWF	0.78**	0.77**FF	524	289	3
CM28-MCM-WF	0.79**	0.78**FF	527	285	0

SC, Sørensen's coefficient; K, Cohen's kappa coefficient;

* $P \leq 0.05$; ** $P \leq 0.01$; SC values followed by ** indicate a significant association between burned and unburned areas at $P \leq 0.01$ by χ^2 test; values of K followed by the same letters are not significantly different at $P \leq 0.05$ (one letter) or at $P \leq 0.01$ (two letters) by Z-score test

a, burned area agreement; b, overestimated area; c, underestimated area

The FARSITE simulation obtained with CM28 and CWF map provided a very high K value, equal to 0.77 (SC = 0.78) (Table 15). All the other simulations obtained by FARSITE with constant wind field are positively affected by the effect of the coast line: for this reason the accuracy is good also for the other fuel models, with K values ranging from 0.53 and 0.72 (SC ranging from 0.55 and 0.73). As shown in Table 15, it is confirmed that the SH2 fuel model underestimates the fire area, whereas the other fuel models (SH7, SH5 and FM4) overestimate the fire perimeter.

In Razza di Juncu case study, all simulations estimated the spatial extension of the burned areas better than the random chance, at $P < 0.01$.

The use of raster MCM-WF maps did not allowed an increase in the performances of FARSITE for the burned and unburned areas. For example, for the CM28 fuel model (Figure 62), the use of MCM-WF wind maps did not implemented the K values with respect to the CWF wind map (0.78 vs. 0.78); the same limited improvements in accuracy were showed also by SC coefficient (0.79 vs. 0.78). For all fuel models, the Z-test showed that the differences in K values, when the wind field maps changed, were not significant for $P < 0.05$. Only for the SH2 fuel model the simulations obtained with CWF and MCM-WF are significantly different for $P < 0.05$ (Table 15). This fact is linked with the low differences in the simulated fire areas, because of the presence of the coast line.

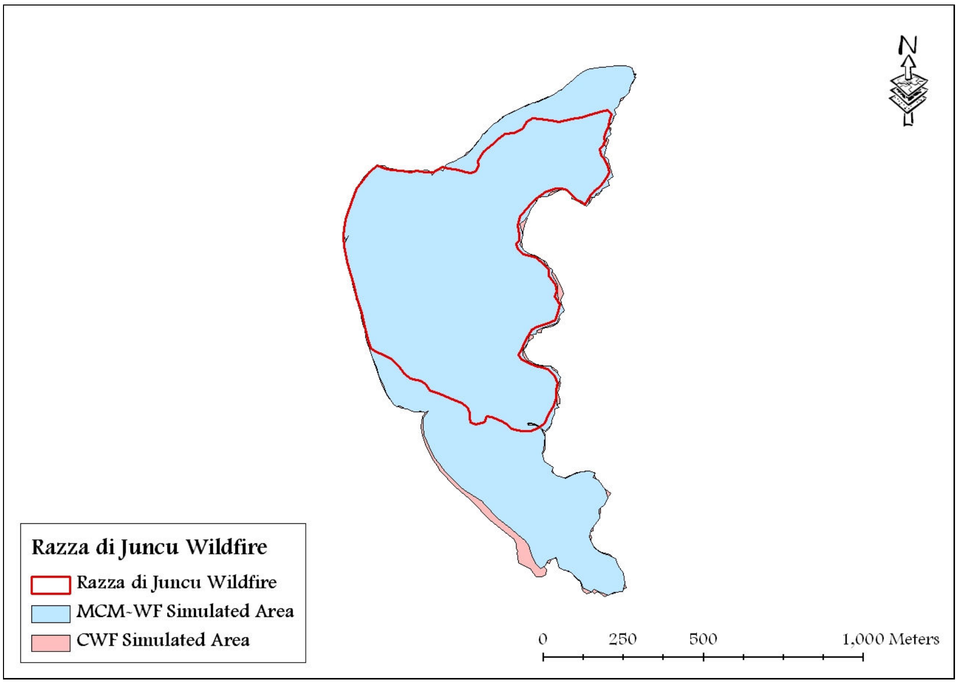

Figure 62. Comparison between observed and simulated fire areas (using CM28 custom fuel model) obtained using MCM-WF maps and CWF maps for the fire event occurred in Razza di Juncu

Therefore, because of the peculiarity of Razza di Juncu wildfire, the agreement between simulated and observed burned area is not a completely exhaustive index able to emphasize the effectiveness of fuel models in order to fit the actual fire.

The rate of spread is more indicative to evaluate Razza di Juncu fire behaviour, because there is a high variability of this parameter among the different fuel models. In Razza di Juncu, the observed fire front rate of spread was approximately 13 m min^{-1}. The SH2 fuel model underestimates the observed rate of spread, because it evaluated the propagation velocity close to 2-3 m min^{-1} (Table 16). The other standard fuel models (SH7, SH5 and FM4) overestimated the ROS, in particular the FM4 fuel model, which reached values ranging from 32.0 and 36.7 m min^{-1} when gridded and uniform wind field maps were respectively used.

Table 16. Observed and predicted average rate of spread (ROS, m min^{-1}) obtained from all the fuel models simulations, using both uniform and NUATMOS wind field, for the fire event occurred in Razza di Juncu

FUEL MODEL	SIMULATED ROS (m min^{-1})		OBSERVED ROS (m min^{-1})
	MCM-WF	CWF	
FM4	32.0	36.7	13.0
SH5	22.7	31.0	
SH7	16.6	20.0	
SH2	2.3	3.3	
CM28	13.0	16.5	

The best performance in predicting rate of spread was obtained using the CM28 fuel model and the raster wind field map produced by NUATMOS, by which the ROS value was about 13 m min^{-1}. The fire perimeter propagation when this fuel model and the MCM-WF map were used is presented in the following Figure 63. The simulation timestep has been set equal to 20 minutes, so each polygon of Figure 63 shows the fire spread for 20 minutes' intervals. These simulated fire expansion and propagation were very similar to those of the observed wildfire, which arrived 40 minutes after ignition at the first beach and 1 hour after ignition at the second little beach of Razza di Juncu area.

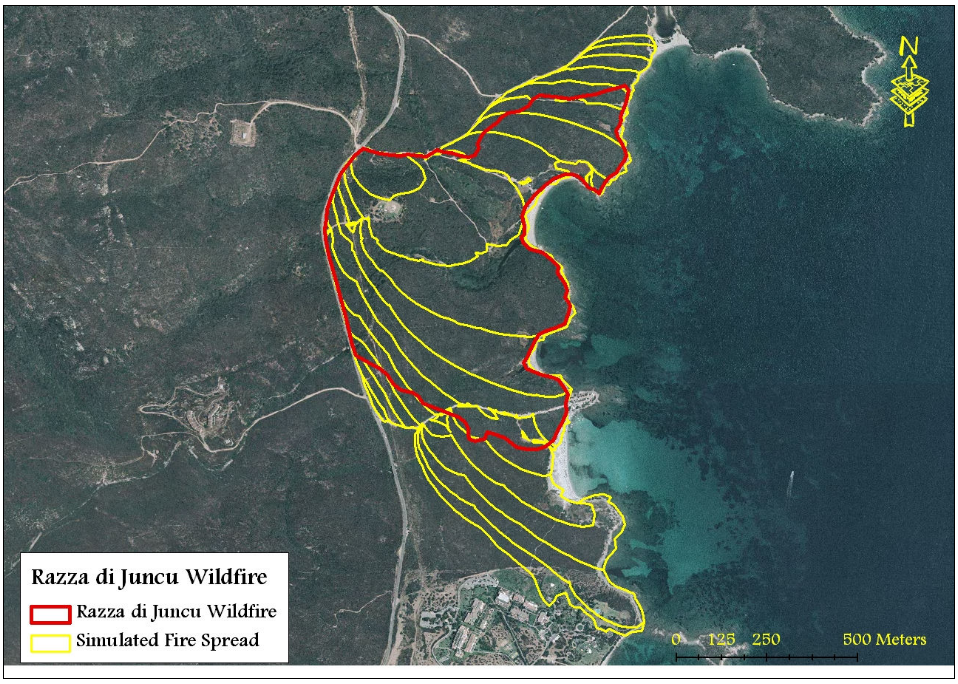

Figure 63. Simulated Razza di Juncu fire spread at 20 minutes' timesteps, using CM28 fuel model and raster wind maps

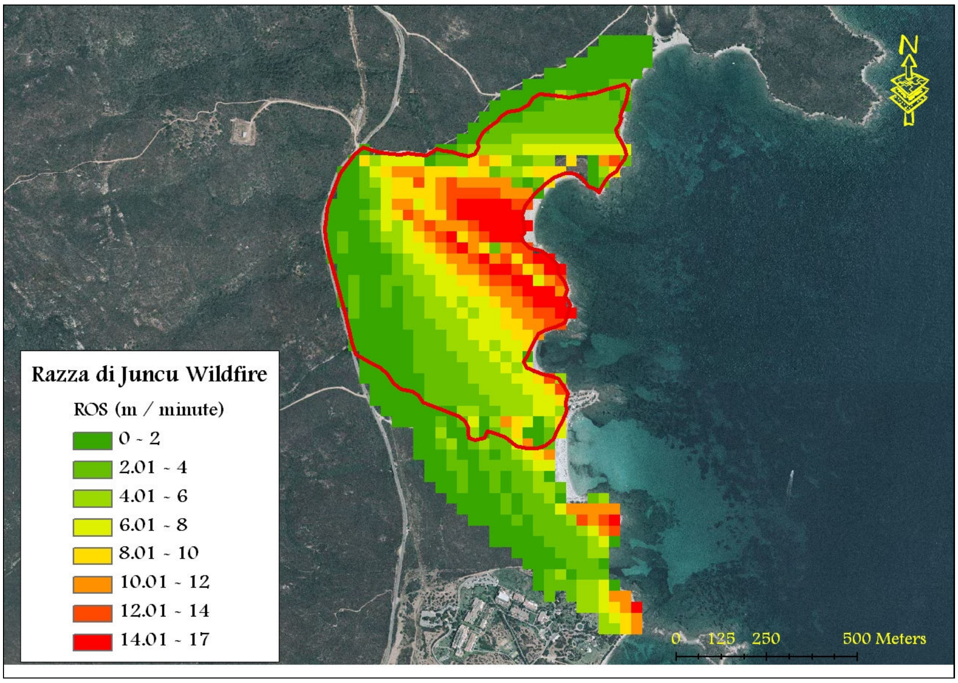

Figure 64. Rate of Spread (ROS, m min^{-1}) predicted by CM28 fuel model and MCM-WF for the fire event occurred in Razza di Juncu

Figure 64 showed the spatial variation of the simulated ROS; the highest values of rate of spread were reached along the prevailing wind direction; in these zones ROS values reached 14-17 m min^{-1}. Because of the flat terrain, the slope did not influence the fire rate of spread. Moreover, a meaningful part of the fire perimeter was burned by flanking fire, which was not able to reach high values of ROS. The best FARSITE simulation (CM28 and MCM-WF map), shown in Figure 63 and in Figure 64, evidenced that the propagation rate by flanking fire has been limited, ranging between 0.1 and 4 m min^{-1}.

19. Monte Pedrosu Case Study

Monte Pedrosu wildfire is the last case study presented in my thesis. This fire burned an area of about 65 ha, and involved a zone mainly covered by Mediterranean maquis. Monte Pedrosu area is actually characterized by uniform shrubland vegetation with different species association (mainly *Pistacia lentiscus* L., *Myrtus communis* L., *Chamaerops humilis* L.) but with mean values of fuel load and plant height slightly inferior with respect to the case study of Budoni.

The fire started in the first hours of afternoon and stopped its spread in late afternoon. The weather was characterized by high temperatures and by a moderate north-eastern wind of about 11 km h^{-1} during the first hours of the event.

All FARSITE simulations were realized by using both a constant wind field (CWF, 11 km h^{-1}) and wind maps obtained with NUATMOS model (MCM-WF), initialized with the wind data of the nearest weather station of SAR network.

The performances of the FARSITE simulations are reported in the next tables (Table 17 and Table 18); the maps of observed and simulated fire perimeters and rate of spread are shown in Figure 65, Figure 66 and Figure 67.

The results reported in Table 17 confirmed that the CM28 custom fuel model, when the MCM-WF maps are used, is the most appropriate to obtain good accuracies in FARSITE predictions of both fire perimeter and spread. This fact is showed by all the statistical analysis summarized in Table 17.

The statistical test showed that the simulation obtained by FARSITE with CM28 fuel model and CWF provided a modest K value equal to 0.36 (SC = 0.47); this simulation is more accurate with respect to the other standard fuel models FM4, SH5 and SH7, which gave K values ranging from 0.08 and 0.14 (SC ranging from 0.26 and 0.31) (Table 17). Only the SH2 fuel model shows a better value of K coefficient (0.40) with respect to the CM28 fuel model; this result can be explained by the low overestimation and the limited underestimation of the burned area. It is confirmed that the worst performances are provided by the simulation with the FM4 fuel model (K = 0.08; SC = 0.26), because of the wide overestimation of the burned area. The overestimation is also confirmed for the SH5 and SH7 fuel models.

Both K and SC values showed that all simulations estimated the burned and unburned fire perimeters better than the random chance at $P < 0.01$.

Table 17. Statistics obtained for different FARSITE simulations on the final perimeter of the fire event occurred in Monte Pedrosu, Italy, on July 15, 2006. The letters a, b, c, refer to the number of cells correctly and wrongly estimated.

Simulation (Fuel Models and Wind Maps)	SC	K	a	b	c
FM4-CWF	0.26**	0.08**A	1663	9277	0
FM4-MCM-WF	0.35**	0.20**B	1663	6086	0
SH5-CWF	0.29**	0.11**C	1663	8303	0
SH5-MCM-WF	0.41**	0.27**D	1662	4848	1
SH7-CWF	0.31**	0.14**E	1663	7306	0
SH7-MCM-WF	0.49**	0.38**F	1662	3501	1
SH2-CWF	0.45**	0.40**G	591	363	1072
SH2-MCM-WF	0.28**	0.23**H	296	190	1367
CM28-CWF	0.47**	0.36**I	1663	3695	0
CM28-MCM-WF	0.86**	0.84**L	1549	406	114

SC, Sørensen's coefficient; K, Cohen's kappa coefficient;

* $P \le 0.05$; ** $P \le 0.01$; SC values followed by ** indicate a significant association between burned and unburned areas at $P \le 0.01$ by χ^2 test; values of K followed by the same letters are not significantly different at $P \le 0.05$ (one letter) or at $P \le 0.01$ (two letters) by Z-score test

a, burned area agreement; b, overestimated area; c, underestimated area

All the statistical tests reported an important increase when the MCM-WF maps were used: the increases in K and SC values were significant for $P < 0.01$. This case study confirms that the use of NUATMOS, in order to evaluate the wind field during the burning period, permits an improvement of the results for all the maquis fuel models tested. In most of the simulations the use of raster maps doubles the agreement among simulated and observed fire areas (Table 17). The fire perimeters obtained by the main simulations are presented in the next Figure 65 and Figure 66.

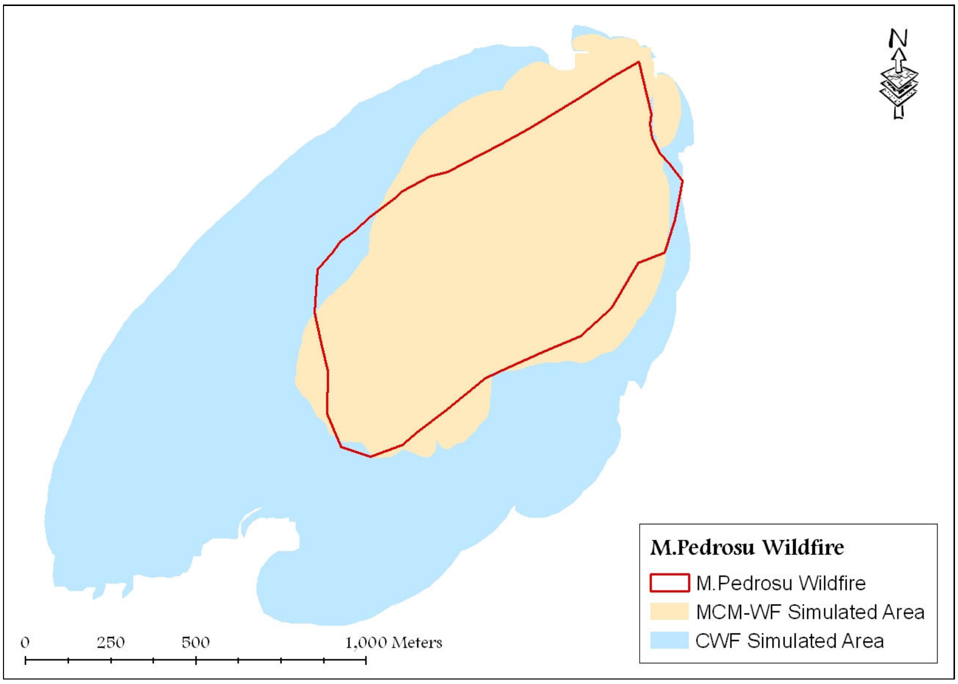

Figure 65. Comparison between observed and simulated fire areas (using CM28 custom fuel model) obtained using CWF and MCM-WF for the fire event occurred in Monte Pedrosu

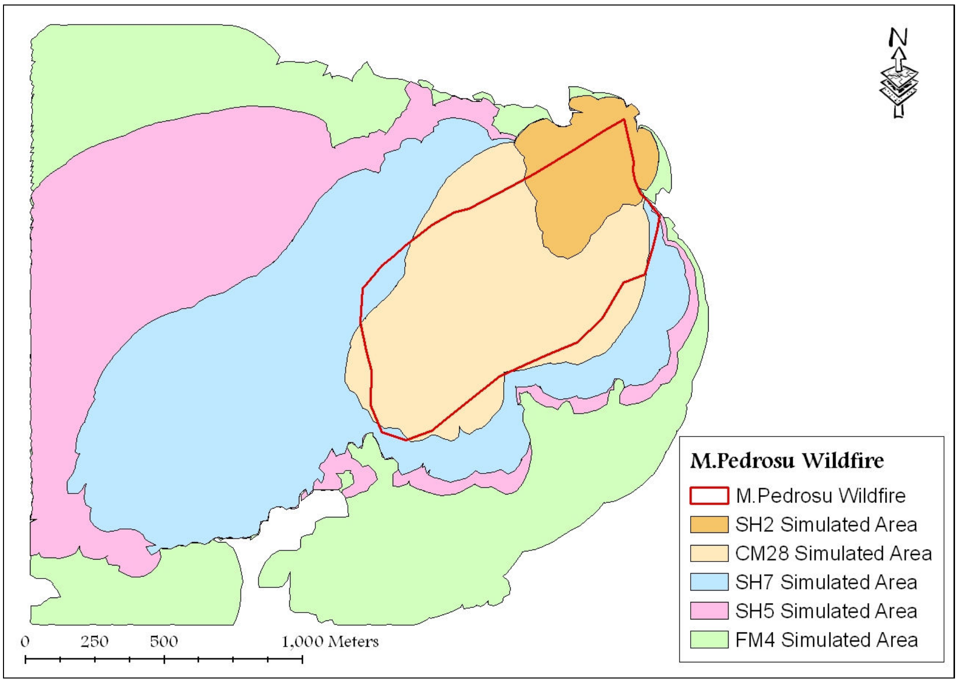

Figure 66. Comparison between observed and simulated fire areas (with MCM-WF maps) obtained using custom and standard fuel models for Monte Pedrosu wildfire

For example, when the CM28 fuel model and the MCM-WF maps are used, K value is equal to 0.84 (SC = 0.86); this coefficient comes down till 0.36 (0.47 for SC coefficient) when uniform wind field is used for FARSITE simulations. This good agreement is linked with the small overestimation and underestimation of the burned perimeter. Also for this case study the good performance of the CM28 fuel model and the MCM-WF maps can be explained by considering the orographic characteristics of the burned area, that did not shows important variations for slope and elevation, with respect to Budoni, where the down-slope wind conditions were present.

The analysis of predicted and observed fire rate of spread is important to consider the differences among different fuel models. The observed final rate of spread of Monte Pedrosu wildfire was about 4.6 m min^{-1} (Table 18). Also for this case study of Monte Pedrosu the best performance in predicting the propagation rate of fire was obtained using the CM28 custom fuel model and the MCM-WF maps produced by NUATMOS, by which ROS value is approximately equal to observed ROS value. The other standard fuel models presented ROS values higher than CM28 simulated ROS, both for constant and raster wind maps; only the SH2 fuel model shows ROS values very limited (Table 18).

Table 18. Observed and predicted average rate of spread (ROS, m min^{-1}) obtained from all the fuel models simulations, using both uniform and NUATMOS wind field, for the fire event occurred in Monte Pedrosu

FUEL MODEL	SIMULATED ROS (m min^{-1})		OBSERVED ROS (m min^{-1})
	MCM-WF	CWF	
FM4	7.0	13.0	4.6
SH5	6.7	11.9	
SH7	6.5	11.4	
SH2	1.6	2.1	
CM28	4.6	8.3	

The observed maximum rate of spread of Monte Pedrosu wildfire reached approximately 4-5 m min^{-1}. As shown in Figure 67, for this case study the highest values of rate of spread were located along the wind direction line, reaching maximum values of 10-12 m min^{-1}; these maximum values were reached in proximity of a little hill, where the slope of terrain was increasing. Most part of simulated fire rate of spread was lower than 4 m min^{-1}, in particular in the flanking parts of perimeter.

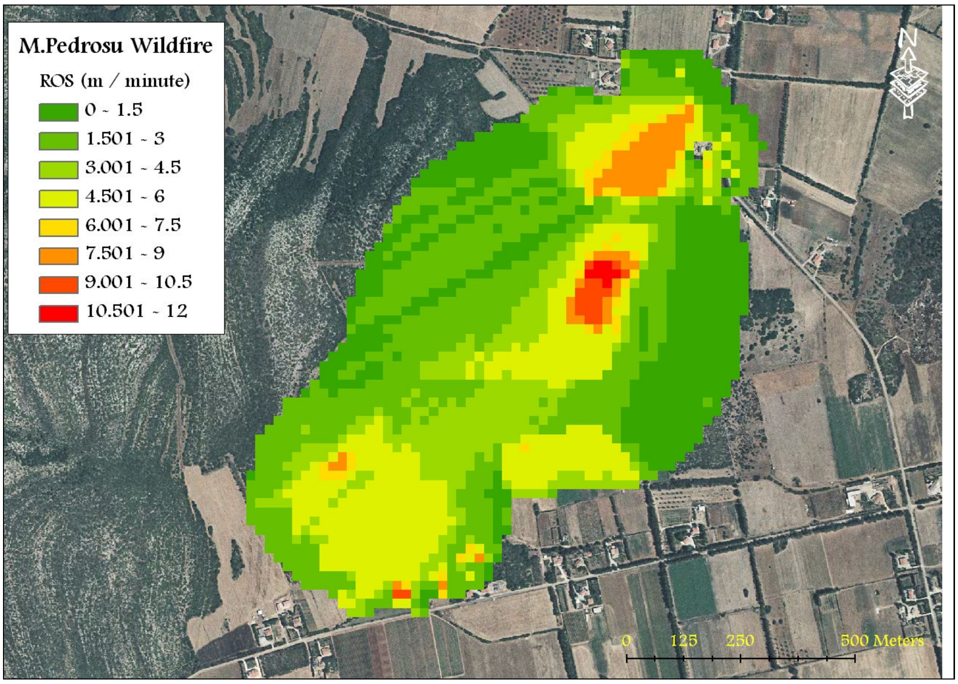

Figure 67. Rate of Spread (ROS, m min^{-1}) predicted by CM28 fuel model and gridded wind field for the fire event occurred in Monte Pedrosu

CONCLUSIONS

In my thesis, the performances of FARSITE simulator in Mediterranean areas where shrubland vegetation is predominant were evaluated.

The accuracy of FARSITE was improved using a custom fuel model (CM28) designed and developed with the purpose of simulating the fire spread rate and behaviour on this type of vegetation.

The custom fuel model presented in my thesis is characterized by a higher live to dead fuel ratio, in comparison with the standard fuel models FM4 by Anderson (1982), and SH2, SH5 and SH7 by Scott and Burgan (2005), and it includes a more balanced combination of the 1, 10 and 100 hr dead fuel loads.

As reported by other authors (van Wilgen et al., 1985; Dimitrakoupoulos, 2002), our results suggest that specific custom models need to be developed to account for both the fuel characteristics and the high heterogeneity of shrubland vegetation.

Weise and Regelbrugge (1997) reported an overestimation of actual fire spread in chaparral using the standard fuel model FM4, demonstrating that the accuracy of the simulations can be improved by developing and using specific custom fuel models.

Van Wilgen et al. (1985) suggested the development of different custom fuel models to accurately describe the heterogeneous structural types of fynbos.

The parameters of our custom fuel model are in agreement with several studies conducted to determine the fuel types of Mediterranean vegetation.

In relation to the distribution of fuel load on different size classes (1, 10 and 100 hr), Dimitrakopoulos (2002) described the characteristics of two Mediterranean shrubland (maquis) fuel models, indicating that 10 and 100 hr fuel load were significantly represented.

In addition, Baeza et al. (2002) showed the effect of plant age on the fuel load in large size classes.

As reported by Sun et al. (2006) for chaparral fuel, dead and live vegetation show differences in burning characteristics. The authors emphasized the importance of determining the effect of live chaparral on fire behaviour.

Dimitrakopoulos and Papaioannou (2001) classified the foliage of the same species studied here as moderate flammable and flammable, even at high values of live moisture content. In addition, they showed the relevance of the relation between moisture of extinction and presence of essential oils, which are important factors in propagating the fire when the plant moisture content is high.

The effect of essential oil concentration on live vegetation fire spread was also reported in previous studies (Pyne, 1984; Wilson, 1985).

Several authors discussed the use of Rothermel's fire spread model in Mediterranean areas.

Zhou et al. (2005b) did not recommend the use of this model in Mediterranean ecosystems (i.e., chaparral), because of the predominance of live fuel.

Limitations of Rothermel's model are particularly clear under low or moderate environmental conditions, typical of marginal burning (Zhou et al., 2005a).

When more severe or extreme environmental conditions occur, the fire behaviour is less affected by the fuel status and depends mainly on fuel type, weather and slope conditions. In these conditions, the intrinsic limitations of Rothermel's model can be overcome by the use of both appropriate custom fuel models and accurate weather data, which are essential to obtain reasonable simulations of fire spread and behaviour.

In my thesis, FARSITE simulator combined with the custom fuel model CM28 gave realistic values of rate of spread, similar to those reported by other authors for Mediterranean shrubland (Weise and Regelbrugge, 1997; Fernandes, 2001).

The results confirm that the performance of FARSITE simulator is affected by resolution and accuracy of wind data (Hanson et al., 2000). Indeed one major source of uncertainty in fire behaviour predictions is the spatial variation in the wind fields used in fire simulators, because in most cases wind data are limited to only a few specific locations, none of which may be actually near the fire location (Forthofer et al., 2003). Improvements of the simulation accuracy could be obtained using high resolution wind field data, calculated by computational fluid dynamic models (Kim et al., 2000; Lopes et al., 2002; Lopes, 2003; Butler, 2005; Forthofer, 2007).

For this purpose, the computational fluid dynamic model NUATMOS (Ross et al., 1988) has been used to rebuild the wind field maps in three wildfire areas.

The main limitation of NUATMOS is linked with the topography of the burned areas, because it is demonstrated that this model does not work properly in complex topography, primarily because it doesn't solve the momentum conservation equation (Lopes, 2003).

In conclusion, the use of both wind field data and appropriate custom fuel models is essential to obtain reasonable simulations of fire spread and behaviour on Mediterranean vegetation during the drought season, when most of the annual wildfires occur.

Information derived by databases of actual fires occurred in Mediterranean areas could improve the accuracy of estimates by an extensive calibration and validation of the simulator.

Further studies should be conducted to analyze the effect of limitations and assumptions of Rothermel's model on the simulation accuracy, and to evaluate the potential of FARSITE simulator in planning the operational phases of fire management in Mediterranean Basin areas.

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