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MAQUIS FUEL MODEL DEVELOPMENT TO SUPPORT SPATIALLY-EXPLICIT FIRE MODELING APPLICATIONS

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Pater locutus est:

"Nolo pecuniam,

hoc, ad majorem consequendam gloriam,

feci"

ABSTRACT

The availability of accurate data on conditions and spatial distribution of fuels, a primary component of fire behaviour and fire risk, have been shown to be critical in many fire studies (development of fire risk maps, modelling fire behaviour and propagation, fuel management in prescribed fire, analysis of the smoke emissions, analysis of the polluting effects, etc.). Moreover, accurate fuel type maps are required input themes for fire behaviour simulation models, for computing fire hazard and fire risk and simulating fire growth and intensity across a landscape. In the last decades, remote sensing techniques become a useful source of spatial data for fuel mapping, offering a wide range of different sensors and algorithms that can support in these efforts.

Several studies focused on fuel characterization and classification, and some of them are currently applied to the management of forestry resources. In several European countries, however, fuel load estimation and fuel model definition are still relevant issues that need to be addressed, in order to improve effectiveness of wildland fire prevention and management. In Italy, for example, there is a lack of studies devoted to systematic analysis of the vegetation characteristics related to fire behaviour and risk.

In this perspective, the aim of the present work is to propose an integrated approach based on field data collection, fuel classification and mapping, with the main objective to provide a set of fuel models for the main Mediterranean maquis associations. In the first phase of the study, the fuel complex characterization was conducted collecting the main fuel variables, analyzing the relationship between fuel complex properties and fuel load, and then classifying the field data into four fuel types. From these fuel types, four custom fuel models were developed and their associated potential fire behaviour was estimated through BehavePlus 3.0. The achieved results have been compared with both standard fuel models, and custom fuel models developed for Mediterranean shrublands, showing similar values of fuel load, but different values of fire behaviour. In the second phase of the work, a supervised classification by the Maximum Likelihood method was applied on an IKONOS image to identify and map the different types of maquis vegetation in Northern Sardinia, Italy. Thus the remotely sensed fuel information, "crosswalking" from the IKONOS fuel type map to fuel model map, was re-sampled

at three different resolutions, and was used as input to a fire spread simulator (FARSITE). The results evidenced that the use of remotely sensed data at high spatial and spectral resolution is a valuable tool in fuel model mapping, and can improve the accuracy of FARSITE simulations, and then the predictive capabilities of the simulator.

SOMMARIO

La conoscenza e disponibilità di dati sulle condizioni del combustibile e sulla sua distribuzione spaziale, primari elementi per la quantificazione del rischio di incendio, è un fattore critico per numerose applicazioni, quali lo sviluppo di mappe di rischio, lo studio del comportamento e della propagazione dell'incendio, le attività di gestione del combustibile mediante il fuoco prescritto, le analisi delle emissioni e gli effetti inquinanti del fumo dovuto alla combustione. Inoltre, le mappe delle tipologie di combustibile rappresentano tematismi di input essenziali per la simulazione del comportamento dell'incendio e per il calcolo delle variazioni spaziali dell'intensità e della severità dell'incendio. In questi ambiti, l'utilizzo del telerilevamento da satellite rappresenta una preziosa fonte di informazioni spaziali utili per la mappatura del combustibile.

Diversi studi hanno avuto come oggetto la caratterizzazione e la classificazione del combustibile, e alcuni di essi sono correntemente applicati nella gestione delle risorse forestali. Ciò nonostante, in diversi paesi Europei, la stima del combustibile e la definizione di modelli di combustibile sono argomenti non ancora affrontati nella loro interezza. In Italia, per esempio, data la scarsezza di studi dedicati all'analisi sistematica delle caratteristiche della vegetazione relative al comportamento del fuoco, spesso vengono usati dati e modelli di combustibile sviluppati in altre nazioni.

Il presente lavoro si inserisce nel panorama così delineato con lo scopo di proporre un approccio integrato di raccolta e analisi dei dati di combustibile relativi alla macchia mediterranea, con conseguente classificazione e mappatura delle principali tipologie riscontrate nella fase di campionamento. Fra gli obiettivi primari del presente lavoro, si pone l'accento sullo sviluppo di modelli di combustibile delle principali tipologie di macchia mediterranea.

In una prima fase della sperimentazione sono stati caratterizzati i complessi di combustibile, attraverso il campionamento delle principali variabili e l'analisi delle relazioni fra le proprietà strutturali dei complessi e il carico di combustibile (peso secco su unità di area). I dati ottenuti sono stati classificati, attraverso la *cluster analisys*, in quattro principali tipologie di combustibile, conseguentemente parametrizzate in modelli di combustibile. Il previsto comportamento del fuoco è stato valutato attraverso l'uso del simulatore

BehavePlus 3.0, ed infine i risultati raggiunti sono stati comparati con altri modelli standard e custom, sviluppati appositamente per vegetazione arbustiva in aree climaticamente mediterranee. Ciò ha permesso di valutare, fra i vari modelli, le similitudini in termini di variabili comparate, e le differenze relative al previsto comportamento dell'incendio.

In una seconda fase dello studio, è stata eseguitala classificazione supervisionata, attraverso l'algoritmo ML (maximum likelihood), della vegetazione mediterranea in Sardegna, di un'immagine satellitare IKONOS. I risultati della mappatura hanno evidenziato che l'utilizzo dei dati telerilevati da satellite ad alta risoluzione spaziale e spettrale possono fornire una valida caratterizzazione e mappatura delle tipologie di combustibile, anche se proprio l'alta risoluzione incrementa la variabilità insita nello spettro e le difficoltà nel valutare l'altezza del combustibile, comportando dunque diversi errori di omissione e commissione.

I dati ottenuti dalla classificazione supervisionata, abbinati ai modelli di combustibile in precedenza sviluppati e ricampionati a tre risoluzioni, sono stati infine utilizzati come input per supportare la simulazione del comportamento e dell'avanzamento dell'incendio attraverso il modello FARSITE (Fire Spread Simulator) I risultati ottenuti hanno evidenziato interessanti variazioni nel comportamento del fuoco, mostrando come la risoluzione delle mappe a scala locale influenzi le prestazioni del simulatore.

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Valentina

CONTENTS

INTRODUCTION

Fire is an integral part of Mediterranean ecosystems (Pausas and Vallejo, 1999), but as pointed out by Susmel (1973), lightening causes wildfire on only 0.6-4% of the annually burned areas, unlike others ecosystems. Evidence that many species are adapted to fire assumes that other forces were causes of fire in the past; although there is no direct evidence of burning by Paleolithic hunters and food gatherers (Stewart, 1956), Naveh (1975) affirms that it is reasonable to presume *"…that, after realizing how natural fires opened the dense and impenetrable forest and maquis […] and created biologically richer ecotones and successional stages, they might have used fire deliberately to facilitate hunting and food gathering […]"*. During the Neolithic human-induced changes by fire in the Mediterranean landscape were more evident (Naveh, 1975), and several authors suggested that the fire became the first tool for ecosystem manipulation (Sauer, 1957; Stewart, 1956; Oakley, 1961). Since then, the Mediterranean basin saw an evolution of many cultures, most making combined use of fire and farming. Fire played an important and active role in pastoral and agricultural ecosystem modification and conversion, in forest and land clearing for cultivation and apparently also in domestication of cereal crops (Naveh, 1973; Komarek, 1967).

Whereas small fires were part of the natural dynamics, the larger fires, from the 70s until today, showed an increasing trend in number and burned areas in the European Mediterranean areas (mainly Iberian, Italian and Greek Peninsulas and surrounding islands) (Pausas and Vallejo, 1999), due to several causes. On equal terms with climatic conditions, the increasing occurrence of fires is promoted by the land-use changes, such as the increasing rural depopulation and land abandonment. The constitution of mono-specific cultivations, the irrational urbanization in forested areas, and the touristic "invasion" (Bussotti et al., 2005) are also major factors influencing fire dynamics; on the other hand, climatic warming should also be considered as a contributing factor.

In effect, urbanization and increased population resulted in the enhancement in human productive activities, with a remarkable expansion of commercial and industrial activities and communication. It is necessary to take into account all the millennia during which the man settled, burned, cut and grazed, and the more recent centuries of severe human pressure, which resulted in clearing, terracing, cultivating, and later abandonment of arable portions, which created a strongly human-influenced landscape. 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 overgrazing influenced various regions, with changes in vegetation distribution models and landscape dynamics.

Changes in fire occurrence during recent decades closely reflect the recent socio-economic changes underway in the European Mediterranean countries (Vélez, 1993; Moreno et al., 1998). With industrial development, European Mediterranean countries have experienced depopulation of rural areas, increases in agricultural mechanization, decreases in grazing pressure and wood gathering, and increases in the urbanization of rural areas (LeHouérou, 1993). These changes in traditional land-use and lifestyles have implied the abandonment of large areas of farm-land, which has led to recovery of vegetation (García-Ruiz et al., 1996; Roxo et al., 1996) and an increase in accumulated fuel (e.g. Rego, 1992).

In Southern Europe, human activity has dramatically increased fire frequency because of land abandonment and tourist pressure. Piñol and Terradas (1996) found a significant relationship between population density and fire occurrence in Mediterranean areas of the Iberian Peninsula. As a consequence, landscapes are becoming more homogeneous (Moreno and Oechel, 1992; Sala and Rubio, 1994). In summary, land-use changes produced during the present century in southern Europe have affected fire regimes from being few in number and affecting small areas, to becoming numerous and affecting large areas every year.

Climatic factors should be considered also as contributing factor for fire increase in the last decades. Surely, the role of climate variability in affecting human activities and the natural environment is well accepted. This may range from an extreme event lasting only a few hours (e.g. hurricane, thunderstorm, and showers) through to multi-year droughts (e.g. West and Sahelian Africa and Iberian Peninsula drought spells). Climate change due to the enhanced greenhouse effect is also expected to strongly affect these activities and environments. Response of forest ecosystems to climate change can be expressed in terms of boundaries shift,, changes in productivity, and in risk of damages (e.g. fire damage).

Predictions on climate warming in the Mediterranean basin forecast increases in air temperature and reductions in summer rainfall (Houghton et al., 1996). Although there is uncertainty on precipitation changes, all predictions suggest a future increase in water deficit and associated increases in temperature in the summer months, ultimately leading to an increase in water stress conditions for plants, changes in fuel moisture conditions and increases in fire risk. Increases in ignition probability and fire propagation, especially in summer when temperatures are high and air humidity and fuel moisture are low, are also expected (Pausas and Vallejo, 1999).

Some authors analyzed historical climate data showing some of these trends (Maheras, 1988; Amanatidis et al., 1993; Piñol et al., 1998). For example, Colacino and Conte (1993 a, b) examined the pattern of forest fires in the Mediterranean region in connection with the number of heat waves and found increase of 70% in the number of heat waves recorded from 1980–1985, compared to the period 1970–1975, and a similar increase in the extent of forest burned. Piñol and others (1998) analyzed meteorological data from 1910 to 1994 in the eastern Iberian Peninsula, highlighting a clear increase in temperature and potential evapotraspiration and a reduction in summer humidity, correlating to an increase in the number of fires.

Vulnerability of forests will be high in the Mediterranean region due to the decline in summer precipitation, which no longer supports the present forest cover. This negative effect will be further enhanced by an increased fire risk.

These differential trends make the European Mediterranean Basin more fire prone, as shown in the fire statistics of the last decades (Vélez, 1997a; Moreno et al., 1998). But it is only with the last years' extreme fire seasons that the focus on how land management activities affect fire ecology, wildfire risk, and fuel and vegetation dynamics has increased (Andrews, 2001). In effect, in the South-Western European Mediterranean region the last 5 (2000-2005) had a large number of fires and higher burned area (more than 60,000 wildfires per year and about 490,000 hectares of burned areas according to the European Commission, 2006). But it is during the past 2007 summer season that many European Countries experienced the highest fire intensity: in Greece, where the overall burned area in 2007 amounted to 270,000 hectares approximately, of which 180,000 burnt between the 24 and 30 August (European Civil Protection, 2007), more than 60 people died. And also the last summer fire season in Italy, when 140,000 hectares of burned areas mainly in the south of the country were burned (Corpo Forestale dello Stato, 2007). New tools and methodologies are desperately needed to guard, monitor and to fight wildfires in the future.

So far in Europe, and especially in Italy, the main part of suppression efforts is circumscribed to active fire fighting, with a constant development of new technologies and modernization of the old ones. The introduction of more flexible and effective aerial craft, growth of terrestrial forces, which has shown a meaningful benefit with the reduction of burned areas in many Mediterranean regions (Boni, 2004). But, even with an improvement in active fight apparatus, it is still necessary to develop a new fire policy that, from the point of view of land use management activities and climate warming, 1) directs the optimization of resources, 2) decides the priority of the aerial and terrestrial interventions, 3) considers the site characteristics, 4) balances fire suppression capability, and 5) uses fire to regulate fuels and sustain healthy ecosystems (Andrews, 2001).

Fire modeling and information system technology can play a critical supporting role in all of these activities of fire management, assessment of the current situation, projecting into the future, and especially in the evaluation of alternatives (Andrews, 2001), through the incorporation of fire spread and behaviour prediction models, geo-databases of environmental and vegetation information, and sets of decision rules (Salis, 2008). A variety of programs and tools support wildland fire management. For example, several systems help predict fire growth and behaviour, while providing real-time support for suppression tactics and logistics decisions, with special consideration for firefighter safety (Andrews, 2001); fire models can also be used to assess the way that fuel might burn, or determining fire effects and smoke for dispersion and emission estimates (Stratton, 2006).

These decision support systems (DSS) demonstrate the usefulness of fire models to fuel and fire managers. Fire models such as BEHAVE (fire behaviour prediction system) (Andrews, 1986; Andrews and Bevins, 1998; Andrews et al., 2005) and FARSITE (Fire Area Simulator) (Finney, 1994; 1998) are decision support systems that comprise and link multiple empirical and deterministic models or set(s) of mathematical equations to predict fire growth and behaviour (Stratton, 2006), using the Rothermel's fire spread equation (Rothermel, 1972).

The BEHAVE fire behaviour prediction and fuel modeling system was among the early computer systems developed for wildland fire management (Andrews, 2001). It has been updated and expanded, in the now called BehavePlus (www.fire.org), providing a means of modeling fire behaviour (such as rate of spread and spotting distance), fire effects (such as scorch height and tree mortality), and the fire environment (such as fuel moisture and wind adjustment factor). Users of BEHAVE interactively provide input to produce table and graphs. Each calculation is based on the assumption that conditions are uniform and constant for the projection period; but rarely is a single calculation done. In most cases, the effect of a range of values is examined.

FARSITE (Finney, 1994; 1998) is one of the main fire simulation systems developed over recent years. It is a two-dimensional program for spatially and temporally simulating the spread and behaviour of fires under heterogeneous conditions (Stratton, 2006). FARSITE incorporates existing fire behaviour models as the surface fire spread (Albini, 1976; Rothermel, 1972), or the crown fire spread (Rothermel, 1991; Van Wagner, 1977, 1993), and it requires spatial information on fuels, weather, and topography, fuel moisture and weather data. Finally, FlamMap (Finney, 2006) is a spatial fire behaviour mapping and analysis program Unlike FARSITE, FlamMap makes independent fire behaviour calculations, as the fireline intensity, or the flame length, for each location of the raster landscape, independent of one another. FlamMap is a fire hazard analysis tool, not a fire spread simulator, because landscape and weather and wind information are held constant. FlamMap output lends itself well to landscape comparisons (for example, pre- and post-treatment effectiveness) and to identifying hazardous fuel and topographic combinations, thus aiding in prioritization, planning, and assessment (Stratton, 2004).

As discussed above, these simulators are based on the semi-empirical fire prediction model developed by Rothermel (1972) that provided good approximations within the range of conditions tested during the phases of model development and calibration (van Wagtendonk, 1996; Zhou et al., 2005a). The Rothermel model requires the description of the physical characteristics of the surface fuel bed through the fuel model concept (*sets of parameters required that describe the fuel as required by the fire model*), and the first models were based on a series of laboratory experiments conducted using small size and homogeneous dead fuels. Nevertheless, this approach supplied simulation results often unrealistic due to the model assumptions and some experimental limitations (e.g. a limited number of species and fuels were used) (Arca et al., 2007). As highlighted by Cruz and Fernandes (2008), the Rothermel model was developed under near-homogeneous fuel conditions, hence its application to naturally occurring heterogeneous fuels might require adjustment. The use of these simulators as a component of a decision support system for planning the fire management practices involves the assessment of the simulation accuracy under different environmental and vegetation conditions (Arca et al., 2005). For that reason, several implementations of the above fire models based on Rothermel's model were developed to choose between a set of standard fuel models (Anderson, 1982; Scott and Burgan, 2005), or develop a custom model based on measured or estimated fuel data (Burgan and Rothermel, 1984).

Shrub is one of the most important fuel types in the Mediterranean region, therefore numerous studies on fire-prone communities have been conducted to establish the relationships between fire, specific vegetation composition and structure (Papiò and Trabaud, 1991; Pereira et al., 1995; Baeza et al., 1998). As a consequence, it is fundamental to correctly characterize the fuel under different environmental and vegetation conditions to obtain valid fire simulations helpful in all aspects of fire management. At the beginning of fire research, the fuel assessment was a *qualitative* analysis (e.g. Barrows, 1951), but now fire models provided a means of *quantitative* analysis, introducing the concept of using fuel models to characterize fuel for fire managers. The relative inputs required by fire models can be categorized as fuel parameters, including heat content, mineral content, particle density, moisture of extinction, loading by size class for live and dead fuel, mean size within each class measured by surface-area-to-volume ratio, and mean depth of fuel. A fuel model describes the physical characteristics of the fuel, rather than the species (Scott and Burgan, 2005). Fire behaviour fuel models describe the fine fuel that carries fire spread, as required by Rothermel's model. Designing a fire behaviour fuel model is an iterative process of comparing predictions to observed or expected fire behaviour and adjusting the fuel model parameters until a satisfactory result is achieved (Burgan and Rothermel, 1984; Burgan, 1987).

Knowledge of natural fuel loads (biomass weights) and species composition is critical for improving current fire prevention and fire behaviour modeling programs (Tian et al., 2005). Thus it is necessary to develop fuel inventory systems for the correct catalogue and organic collection of these variables. In the United States, several attempts have been made, from the commonly used dead and down woody fuel inventory system of Brown (1974) which provides a method of quantifying average load by size class of downed woody fuel, to the newest FIREMON (Fire Effects Monitoring) (Lutes et al., 2006), which established a protocol to inventory and monitor the fire effects. It included a set of sampling manuals, database, and analysis programs supplying the necessary tools to develop and design projects regarding monitoring the fire effects, to collect and catalogue the data, and analyze data statistically.

On the other hand, with the development of sensors and advances in satellite technology, remote-sensing techniques, including aerial photography and satellite imagery, are now widely used in wildfire management (Tian et al., 2005), offering a way to provide some of the data needed for fire management and fuel assessment (Chuvieco, 1997). Furthermore, remote sensing can be used for fuel and vegetation mapping (Keane et al., 1998). Fuel-type maps account for structural characteristics of vegetation related to fire behaviour and fire propagation, but also fuel maps are essential for spatially computing fire hazard and assessing fire risk (Keane et al., 2001). Keane and others (2001) reviewed needs and limitations of remote sensing for fuel assessment. They pointed out that, using remote sensing, fuel mapping is an extremely difficult and complex process, because it requires expertise in image classification, fire behaviour, fuel modeling, ecology, and GIS. Nevertheless there are limitations to what remote sensing can provide, the use of remote-sensing data in the classification and mapping of vegetation is becoming the primary method for assessing fuels.

The Department of Economics and Woody Plant Ecosystems, University of Sassari, in collaboration with the Institute of Biometeorology, National Council of Research of Sassari, from several years has conducted a series of research activities regarding the assessment of fire risk in Sardinia, with the development of a fire risk dynamic model (Ichnusa Fire Index) (Pisanu, 2005; Spano et al., 2005; Sirca et al., 2005), and the evaluation of the capabilities of FARSITE simulator to model the fire spread and behaviour (Salis, 2008). In this field of evaluation and assessment of the fire problem in Mediterranean vegetation, the fuel topic turns out to be important and not yet analyzed in its completeness. Therefore, this work focuses on the major fuel topics: (i) the fuel complexes characterization, (ii) the analysis of the relationship between fuel complex properties and fuel load, (iii) the development of a set of fuel models for Mediterranean maquis, (iv) the development of maps of fuel models at local scale by analysis of remote sensed data, and finally (iv) the evaluation of the capabilities of fuel model themes and fuel map in simulating the fire spread and behaviour by spatially and temporal explicit fire simulators.

Following are the description of the most relevant issues addressed by this thesis:

- *Chapter 1: Fuel in Mediterranean Vegetation,* introduces the vegetation of this study, defining first the climatic condition and the general adaptation of the Mediterranean ecosystems, and then focusing on the Mediterranean maquis and on its relationship with fire;
- *Chapters 2, 3 and 4: Fuel Description, Characterization and Classification,* concerns the basis of fuel characterization, from the more fine particles to the entire fuel complexes, considering also the methodologies to collect these informations, and the existing knowledge on developing fuel models;
- *Chapter 5: Fuel Mapping,* in which are described the importance and the need for fuel maps in fire and fuel managements, from the four classical approaches, to the new methodologies, as the integration between remote sensing and biophysical modeling, and object oriented.

1. MEDITERRANEAN ECOSYSTEMS

1.1. Distribution, Characteristics and Dynamics

The Mediterranean ecosystems are characterized by having a climate conditioned by seas and oceans, and a regimen of transition between moderate and tropical-dry climates (Di Castri and Mooney, 1973). The greater part of these uplands is confined to coastal foothills and lower mountain regions, with a Köppen (1923) CS "olive climate" – dry, hot summer with wet, mild winters. This largely subhumid zone can be further divided into a subzone merging into subdesert, and into a slightly wetter, cooler, accentuated thermo-mediterranean subzone merging into the humid, attenuated thermo-mediterranean zone (UNESCO, 1963). The most relevant aspect of the Mediterranean climate is the seasonal periodicity defined also by a non homogeneous precipitation distribution, and by the mitigating effect on the thermal regime due to the ocean currents.

The Mediterranean climate is also characterized by a marked seasonality, with a fresh and rainy period alternating with a warm and dry time. Between these two periods, there are two seasons with intermediate characteristics. Key elements of this climate are:

- The sea and the oceans exercise a meaningful mitigating effect on the thermal regimen, so the temperature range is modest regarding continental climates (Bussotti and Schirone, 2001).
- Mild winter, with minimum temperatures rarely under 0 °C; summer warm and dry, with maximum temperatures lower than 50 °C; the annual medium temperatures range between 14 and 20 °C (Pignatti, 1995).
- The precipitations are variable, reaching annual values ranging from 250 to 1300 mm; they are concentrated in the winter period, whereas in the warm period the rainfall is poor, or almost null.

These climatic conditions are found 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 (Figure 1), with excursion to the 45° parallel north and 30° parallel south. In particular, in the Mediterranean Basin region, because the extension of the Mediterranean Sea from east to west, in terms of surface or longitude, a great part of the regions are touched by this sea benefit of climate that otherwise would interest only the western regions of the Iberian Peninsula and Morocco. This climatic region is extended on three continents and beyond 20 states.

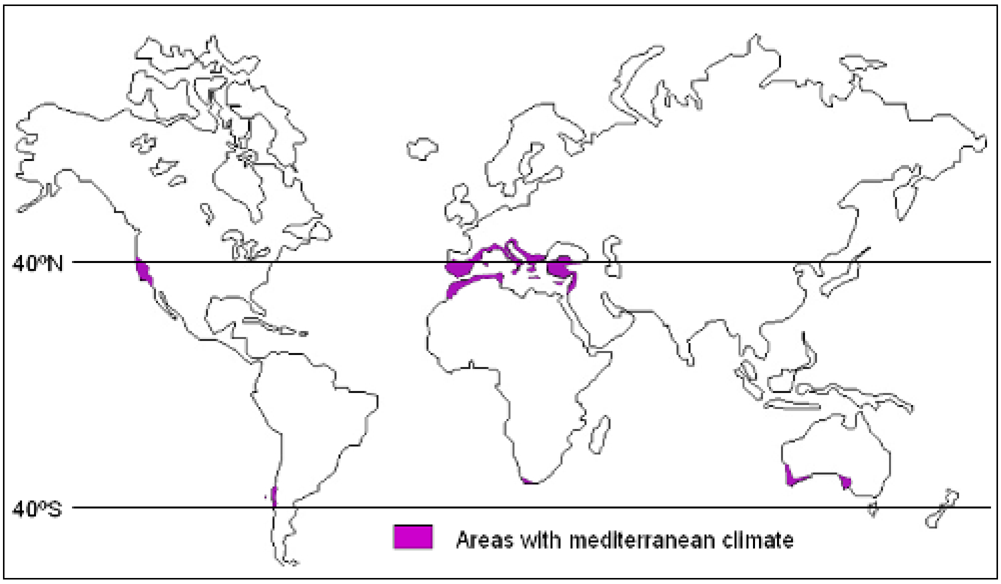


Figure 1. Map of the areas characterized by a Mediterranean climate (from http://it.wikipedia.org)

Given the remarkable variability of climatic factors, and geomorphologic features of the Mediterranean area, it is not possible to refer to an ecosystem or representative biome only, as it happens in other areas of the world. The Mediterranean biome, therefore, is an ecosystems ensemble, each of which has unique environmental conditions. The more representative scheme puts Mediterranean phytocenosis[1] in relation to altitude and the continental climate. In general terms, the Mediterranean ecosystems belongs mainly, according to Mayr-

[1] The term phytocenosis, or vegetal association, refers to the biocenosis ecosystem vegetal component. A phytocenosis exam is fundamental for habitat characterization, habitat dynamic studies, evaluation of evolutive potential, and the conservation needing.

Pavari's classification (De Philippis, 1937), to the phytoclimatic Lauretum zone, in the warm subzone of the *Castanetum*, and more rarely in the cold subzone.

In ecosystems, the maximum degree of development and equilibrium that a vegetation community can reach is often named *climax*: in this phase the vegetation can take advantage of the solar radioactive energy in the best way. Following an increasing order of altitude, in the Mediterranean zones 5 climax can be distinguished (Coastal Zones, Oleo-Ceratonion, Mediterranean Maquis, Mediterranean Evergreen Forest, and Mediterranean Deciduous Forest) (De Philippis, 1937). The Mediterranean Maquis occupies the fresher zones of the Lauretum, characterized from a discreet annual rainfall but with periods of extended drought. Thermophylic species prevail in the floristic composition, with a minor incidence of the xerophytic.

The secondary formations, derived from the above climax, can be joined to this main scheme: those associations are in a dynamic stage of degradation or evolution towards the real climax formations. Among these secondary formations, the *garigue*, the *steppic grassland*, the *secondary maquis* (which can assume different features in relation to prevailing species) can be mentioned. The prairie and the garigue represent the final stages of degradation, and the prelude to the desertification in Mediterranean environment. Whereas, the secondary maquis represents an involutional stage of the Mediterranean shrubland, which can evolve and originate the Oleo-Ceratonion, the Mediterranean Maquis, or the Mediterranean Forest, in relation to environmental conditions and vegetation characteristics. The most common causes that lead to the secondary maquis have anthropogenic origins, namely deforestation, wildfires and overgrazing, which often is successive to the first two elements and provokes an ulterior regression of the vegetation (Gaudenzio and Peccenini, 2002).

1.1.1. Adaptations to climatic conditions

Mediterranean species have developed several strategies to survive during long periods of dryness, such as resistance strategies and tolerance strategies; the first consisting in a set of mechanisms that the plant activates to avoid the stress, whereas the second permits the plant to go through the normal vital functions even if in water deficiency conditions (Bussotti et al., 2005). The most important resistance adaptations are:

- canopy reduced development in several aspects, as small and less numerous leaves, shrubby *habitus*;
- leaves of tough consistency, because of cuticle thickening;
- thorns and hair presence, more or less marked;
- ability to close stomata in conditions of water stress;
- ability to enter into vegetative dormancy in the dry season.

These adaptations are important not only to the humid regime, but also for the thermal regime: in effect, the mild winters, alternated with warm summers, implies that an high number of species is protected mostly from the effects of high temperatures. One of the most studied adaptations to the Mediterranean climate is the sclerophyll, that is the leaves thickening, stickiness (Di Castri, 1981; Bussotti and Schirone, 2001). As pointed out by Bussotti and others (2005), the sclerophyll is a water deficit adaptive response, typical of Mediterranean climates, but it is also observed in other species present in humid and warm regions. Therefore, it is probable that this adaptation is derived from species used to a more humid climate, and after differentiated to more dry areas. The leaf structure is characterized by thick cuticles and dense mesophyll, within several layers of palizade, so the inter cells space is minimal, implying difficulties with gas exchange. This structure is to protect the leaf from excessive evapotranspiration, but at the same time, photosynthetic efficiency is reduced, as is growth. The transpiration is also limited through the mechanism of stomata regulation (the ability to close the leaves stomata) during the hotter day time hours (Peressotti and Magliulo, 1999), in conditions of water stress; nevertheless when the lack of water availability is prolonged during several months, it is possible to observe the plant entering into vegetative dormancy, often during the dry and hot season, and starting again with the photosynthetic activity in autumn.

There is a marked difference in solar incidence between winter and summer in the Mediterranean belt. The solar incidence is elevated from spring to the beginning of autumn, coincident with a period in which the sky is generally clear. Therefore, the vegetation of Mediterranean environments is high in light conditions for much of the year. This aspect becomes more marked in impacted environments, with grounds exposed to the South, in the boreal hemisphere, or to North in the Austral. Moreover, a significant influence in *albedo* can be present, due to stony grounds or emerging cliffs, derived by specific geologic formations (granitic matrix or compact limestone grounds). In relation to the light conditions, the plants are distinguished as heliophylous and sciaphylous. The heliophylous are particularly demanding in light and tolerate little shadowing. The sciaphylous are adapted to low luminous intensities. In some ecosystems, such as those dominated by *Quercus ilex*, the woody vegetation cover is elevated putting the understory in insufficient light conditions. These ecological niches can therefore be occupied by sciaphylous species.

1.2. Mediterranean Maquis characteristics

The shrub formations of Mediterranean basin are locally given specific terms: *macchia* in Italy, *maquis* in the francophone countries, *matorral* in Spain and Chile, *chaparral* in California, *mallee* in Australia, and *strandveld* and *renosterveld* (depending on dominant floral composition) in South Africa (Gaudenzio and Peccenini, 2002; Zhou et al., 2007). When shrub vegetation is low and open, 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 South African vegetation dominated primarily by *Erica*.

The Mediterranean vegetation formation is characterized by a complex floristic association, in which the vegetation is stratified on three levels, optimized by natural equilibriums, which allow the maximum degree of exploitation of incident light on the three levels:

- a high level, established by a woody plant canopy;
- an intermediate level, shaped by shrubby or bushy plants;
- a low level, formed by herbaceous vegetation.

Several attempts to classify the Mediterranean vegetation were developed. Specht's vegetation classification (1970) uses growth form, vegetation height, and foliage cover of the tallest stratum, to distinguish vegetation types (Table 1). Growth forms (trees, shrubs and grasses) are used to describe the structural form of vegetation. The height component is used to describe the basic type, such as forest, scrub and heath, and the foliage cover of the tallest stratum is used to describe the openness of vegetation at a given height.

Table 1. Specht (1970) vegetation classification based on growth form and vegetation height

Growth form of the tallest stratum	*Foliage cover of the tallest stratum (%)*			
	> 70	*30 - 70*	*10 - 30*	*< 10*
Trees 10-30 m	Closed forest	Open forest	Woodland	Open woodland
Trees < 10 m	Low closed forest	Low open forest	Low woodland	Low open woodland
Tall shrubs > 2 m	Closed scrub	Open scrub	Tall shrubland	Tall open shrubland
Low shrubs < 2 m	Closed heath	Open heath	Low shrubland	Low open shrubland

This classification describes vegetation comprised of trees as forest when the height is greater than four meters and the foliage cover is greater than 30%, and woodland when the foliage cover is less than 30%. Since this classification scheme uses characteristics of the tallest stratum, area with both significant shrub layers and emergent trees will be labeled according to the form of the trees (Plucinsky, 2003).

Another classification scheme considering the vegetation height makes it possible to distinguish vegetation into two different maquis type:

- High maquis, in which the tallest vegetation layer is mostly composed of species with woody *habitus*, with the canopy up to 4 meters. For example, in the Italian woody maquis, the most representative species are: *Quercus* genus, section suber (*Quercus ilex* and *suber*); *Phyllirea* genus (ilatro and ilatro), *Arbutus unedo*, some species of the *Juniperus* genus (in particular red Juniper), *Pistacia lentiscus* and others species with minor spread. This maquis is extended in the best pedoclimatic conditions, evolving towards the *Quercus ilex* climax or the evergreen Mediterranean forest.
- Low maquis, where the tallest vegetation layer composed mostly ofspecies with shrubby *habitus*, and canopy up to 2-3 meters maximum. For example, in the Italian shrubby maquis, the species most representatives are: *Pistacia lentiscus*, *Erica arborea*, *Arbutus unedo*, *Myrtus communis*, and other bush as *Cistus species* and *Rosmarinus officinalis*.

Whereas, considering exclusively the floristic composition, it is possible to differentiate the following main formations, according to Bussotti and others (2005):

- *Quercus coccifera* maquis, diffuse in Spain and Southern Italy (Sicily and Puglia regions);
- *Juniper* maquis, coastal dunes in Southern Italy (Sicily and Sardinia regions);
- *Pistacia lentiscus* and *Olea oleaster* maquis, the most diffuse thermofilous formation of coastal maquis, with some variants with *Calicotome* and *Euphorbia dendroides*;
- *Erica, Cistus* and *Lavandula*, representing a stage of degradation before the garrigue, developed on acidic soils, with frequent fire occurrence.

1.2.1. Mediterranean Maquis and Fire

Wildfires have major influences on the structure and function of most Mediterranean type ecosystems (Mooney, 1977). Since the Mediterranean vegetation has always been subject to recurrent fires (Naveh, 1975), mostly of anthropic origin, fires are a common feature and they have long played an important role in the ecology and evolution of flora. Therefore, the fire can be considered as an environmental element, or as defined by McArthur (1966), fire is a key element in the life cycle. At present, fires represent one of the main threats to the Mediterranean ecosystems: currently, the fires are the main disturbance to the Mediterranean forest environment (Velez, 2000). The Mediterranean regions experienced burned areas ranging from 600,000 to 800,000 hectares, and only in Italy, the covered surface, between the 1970 and 2003, exceeded 16 times 100,000 hectares and 3 times (1981, 1983 and 1993) 200,000 hectares.

Fire has a dual role in the Mediterranean ecosystems, being both one of the main disturbance for Mediterranean vegetation, or influencing vegetal community composition and structure, conditioning their evolution and germination (Bussotti et al., 2005). For example, if fire occurrence follows periodic intervals, ecosystems are able to re-establish in relatively short times, due to several defensive strategies that the plants have developed. However, with increasing anthropic pressure, fires often reach enormous sizes, with high frequencies, preventing vegetation recovering and reducing ecological benefit.

As mentioned, vegetation of the Mediterranean region is characterized by several typologies due to the species combination (trees, shrubs, and herbs) and structural characteristics. Thus, the effects of fire on vegetation are very complex, not only because of the great complexity of Mediterranean ecosystems and the interactions with land-uses, but also because of the different responses to different type of fires and fire regimes (i.e., different intensities, seasonalities, recurrences and extent of fire) (Pausas and Vallejo, 1999). These parameters are closely related: for example, an increase in one of the fire components can raise the presence in the communities of several species which are highly flammable and invasive, allowing the possibility of fire reoccurrence. In addition, at the landscape level, post-fire regeneration would depend mainly on the initial vegetation, that is, plant traits of the initial species occurring on the site, and onsite environmental factors (climatic and terrain parameters) (Pausas and Vallejo, 1999).

Fire effect on Mediterranean vegetation

Any plant can be killed directly by a fire of sufficient severity; therefore, as mentioned above, Mediterranean vegetation have developed several defensive strategies to fire offence, allowing the plants to survive. Inherent abilities of plants to survive fire depend largely on their tolerance to heat and their resistance to fire: *heat tolerance* refers to the ability of plant tissue to withstand high temperatures, while *fire resistance* is the ability of vegetation to survive the passage of fire. A plant is killed directly by fire when the temperature of the internal living cell is raised to a lethal level. Generally, the temperature at which plant tissue is killed is largely dependent on the tissue moisture content (Wright, 1970), thus tissues with higher moisture content are generally killed at lower temperatures and in a shorter time. Not only is heat tolerance related to tissue moisture content, it is also different for different parts of a plant (Zwolinski, 1990; Whelan, 1995). In considering seeds, for example, some of them are inherently tolerant to heat. Others seeds have hard, thick seed coats and, as consequence, are able to tolerate high temperature. Roots, bark, and foliage also vary in their relative heat tolerance. Variations in heat tolerance can occur with the presence of sugar, pectins, and other plant tissue substances.

Concerning the traits that confer fire resistance to woody plants, those that insulate or protect the buds and meristem tissues of the plant and those that add to, or conserve, food reserves of the plant are important (Zwolinski 1990; Whelan 1995; Pyne 1996). For example, one of these traits is bark thickness (e.g. *Quercus suber*, Figure 2), a primary factor that determines whether a tree or shrub species is fire resistant. Trees and shrubs suffer little heat damage if their bark thickness is 1.0 to 1.3 cm (Wright and Bailey, 1982). Bark tends to be relatively thin in young, small trees and shrubs, but becomes thicker as plants mature, and finally declines with plant senescence.

Figure 2. Bark thickness in *Quercus suber*

Another trait is bud protection: in effect, fire resistance of a plant is frequently attributed to the location of meristems and protection that buds receive from lethal temperatures. Exposed locations of terminal and lateral apical buds of many small trees and shrubs species make them highly susceptible to top-killing from fire, while plants with surface and subterranean buds are protected. Conversely, the basal meristems of many grass and forb species provide a fire-survival advantage. It must take in account, moreover, that fires play an essential role in the reproductive strategies of most Mediterranean type species. Therefore, the defensive mechanisms are often also reproductive strategies. There are a variety of plant responses to fire, which have been summarized by Gill (1975; 1971a): some Mediterranean species "were forged" and evolved acquiring resistance to the fire, and others even "need" occasional wildfires to survive. The more known mechanisms are the capacity to resprout after fire (resprouter species), and the stimulation of recruitment by fire (seeder or recruiter species).

This main mechanism may occur in a specie at the same time. Pausas (1999) considers four possible combinations: resprouters without recruitment stimulated by fire (R+S-), resprouters with recruitment stimulated by fire (R+S+), non-resprouters with recruitment stimulated by fire (RS+, obligate seeders) and non-resprouters without recruitment stimulated by fire (R-S-).

Species showing adaptation to fire, based on the traits discussed above, are called *pyrophytes*, and differentiated as *active* or *passive* according to the scheme reported in Table 2.

Table 2. Species grouping based on fire adaptations

Pyrophytes	*Strategies*	*Mediterranean Species*
passive	several adaptation to survive (e.g. thick bark)	*Quercus suber*
vegetative active	resprouting	*Arbutus unedo, Pistacia lentiscus, Erica spp*
generative active	germination	*Pinus halepensis, Thymus capitatus, Cistus spp.*

In general, the resprouter species are characterized by maintaining some live biomass (often below-ground biomass) and quickly recovering from fire, and *resprouting* the aerial part. This is a common practice in some trees (e.g. *Quercus coccifera*, kermes oak, dominant species of the garigues) and shrubs (e.g. *Erica spp, Arbutus unedo*) after that fire destroyed their foliage and small twigs. An inhibiting factor of some kind apparently prevents bud activity while foliage is alive, but this inhibition disappears and dormant buds begin sprouting when the foliage is killed (Chandler et al., 1993). Resprouting after fire is generally related to age of the plant, stem size, season, fire frequency, and fire severity.

The recruiter species rely on the *germination of seeds,* which are stored in the soil, stimulated by the heat that is generated by a fire (Mazzoleni, 1989; Shea et al., 1979; Takahashi and Kikuchi, 1986). Compared to the resprouter species, the seeders recovery of non-resprouting species is slower and depends on the fire interval, the age of maturity (to produce seeds for regeneration) and seed longevity, and resistance to fire. Examples of species with fire-stimulated germination are most of the *Cistaceae* and *Papilonaceae* (legumes) species (e.g. Thanos et al., 1992;

Arianoutsou and Thanos, 1996). Furthermore, it has been postulated that post-fire vegetation may be rich in legume species because their capacity to fix nitrogen may alleviate nutrient losses caused by fire. The germination of seeds from some plant species on recently burned sites is also attributed to release of seeds retained by the plants. This trait (fire-induced seed dispersal), known as *serotiny*, is frequent in other Mediterranean type ecosystems (South Africa, Australia) but in the Mediterranean basin it is only found at a relatively low level in a few species such as the Mediterranean pines (e.g., *Pinus halepensis*, *P. brutia*). In these pines the recruitment is stimulated by fire because of increased seed dispersal rather than germination stimulation (Pausas and Vallejo, 1999). Eventually, there are some species which have both the capacity to resprout after fire and to have their recruitment stimulated by fire (e.g. *Thymus vulgaris*, *Anthyllis cytisoides*, *Dorycnium pentaphyllum*) (Pausas and Vallejo, 1999), but in these cases both factors are usually developed to a lesser degree.

Fire regimes

Effectiveness of fire adaptive traits in protecting plants should also be considered in terms of the sequence of natural fires, each with different characteristics and effects, rather than a single fire occurrence. The sequence of fires is referred as *fire regime*, a central concept to the ecological role of fire, described using four components: 1) type, 2) frequency, 3) intensity, and 4) season of fire (Gill, 1975). The *type of fire* refers to its location in relation to the ground surface. Fires in Mediterranean type ecosystems are usually surface fires that burn the entire foliage of trees and shrubs. In North America, the term crown fire ecosystem (Moritz, 2003) was used, describing those fuel types, which experience large scale stand replacing crown fires, inevitable consequence of the structure of shrubby fuels.

Fire frequency is the length of fire frequency between fire intervals, and as highlighted by Gill and others (2001), it is important to the consequences of fire for time-dependant life history processes, such as seed production in plants. In other words, a plant species can be eliminated from a site if fire occurs too often, too early, or too late in the plant's life cycle. Therefore, fire frequency is important in determining which species will continue to occupy the site. High frequency fire is mainly due to the ability of fuels to accumulate quickly after fire (Plucinsky, 2003).

In effect, the defensive mechanisms mentioned in the previous paragraph allow the precedent composition reconstitution according to the frequency, and severity of fire. Species that sprout are generally able to withstand repeated fire, while those plants that produce seed are favored by infrequent fire (Keeley, 1981). Very frequent and intense fires can deplete the seed bank, causing ulterior damages to those species that propagating only by sexual means.

Fire severity refers to the duration and extent of burning. Plant responses to fire severity and duration of heating are variable. Low severity fire can damage late reproduction in plant communities dependant on fire for renewal. The extent of the area burned can also affect plant survival and flowering when the species is unable to regenerate by sprouting. Often the term *fire intensity* is somewhat related to fire severity, defined as the rate of heat released per unit length of fireline.

Finally, the *season of fire* affects the occurrence of fire, which also affects plant survival and flowering. Season is often linked to intensity, with low fire intensity occurring during cool months. In summer fire propagation is favored by warm-dry meteorological conditions, increased wind intensity, and typical Mediterranean vegetation moisture condition, which in summer has the highest degree of flammability. The combined effect of the four fire regime components, and the influence of different post-fire strategies determine landscape characteristics (Margaris, 1980) producing several demographic modalities. Among the fire regime components, fire frequency and severity are probably the more important attributes in terms of ecology, having the greatest effect on plant community composition. For example, Keeley (1986) showed that species surviving low intensity fire with an important seed pool increase their population density essentially during the first year; whereas resprouting species show little changes in their demography (Figure 3, a and b).

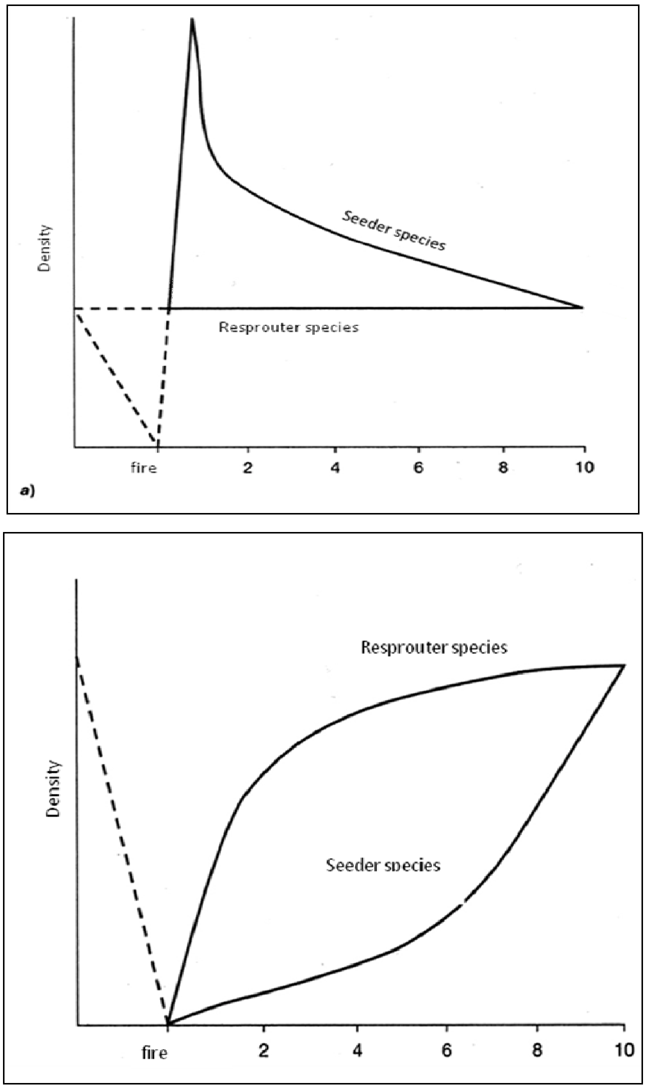


Figure 3. Demographic changing of resprouter (a) and seeder (b) species after fire. In x axis are showed the year since last fire (modified from Keeley, 1986)

On the other hand, these species reach their initial cover more rapidly, with a competitive advantage, for the first ten years than the seed regenerating species. Plant regeneration is influenced also by the combination of season and the intensity of fires. For example, regeneration of obligate seeder species (often dominant shrub species) is poor after low-intensity and cool-season burns (Gill and Groves, 1981). Also the fire intensity has an important role affecting fuel accumulation, reaching hazardous levels.

2. FUEL PROPERTIES

Fuels are composed of various components of vegetation, live and dead, that occur on a site (Davis, 1959). The type and quantity will depend upon the soil, climate, geographic features, and the fire history of the site. To a large extent, potential evapotranspiration and annual precipitation changes with altitude and latitude can describe the expected vegetation and have been used to create vegetation maps (Küchler, 1967). An adequate description of the fuels on a site requires identifying the fuel components that may exist. These components include the litter and duff layers, the dead-down woody material, grasses and forbs, shrubs, regeneration and timber. Various combinations of these components define the major fuel groups of grass, shrub, timber and slash.

Fire researchers and managers have long recognized the influence that fuel characteristics exert on fire behaviour and have attempted to incorporate key characteristics into models used to predict fire behaviour. Fuel characteristics can be considered conveniently as a hierarchy of levels of increasing structural complexity (Mc Caw, 1991). The emphasis put on each hierarchy of fuel properties and the measured characteristics will reflect the type of information required, which is, first of all, related to the approach taken to modeling fire behaviour. At the lowest level of the hierarchy are individual *fuel particles* that have specific characteristics having a direct influence on heat transfer and combustion. According to McCaw (1991) the following level in the hierarchy is the *fuel bed*, consisting in arranged particles in defined proportions and structural configurations, generally associated with certain types of fire behaviour. Several fuel beds together constitute a *fuel complex*, which typically is associated with a recognized structural vegetation forms.

For each fuel component certain characteristics must be quantified and evaluated to select a fuel model for estimating fire behaviour. The most important characteristics for each component are:

- Fuel loading by size classes
- Mean size and shape of each size class

- Compactness or bulk density
- Horizontal continuity
- Vertical arrangement
- Moisture content
- Chemical content, ash, and volatiles

Each of the above characteristics contributes to one or more fire behaviour properties. Fuel loading, size class distribution of the load, and its arrangement (compactness or bulk density) govern whether an ignition will result in a sustaining fire. Horizontal continuity influences whether a fire will spread or not. Loading and its vertical arrangement will influence flame size and the ability of a fire to "torch out" the overstory. With the proper horizontal continuity in the overstory, the fire may develop into a crown fire. Low fuel moisture content has a significant impact upon fire behaviour affecting ignition, spread, and intensity; with high winds it can lead to extreme fire behaviour. Certain elements of the fuel's chemical content, such as volatile oils and waxes, aid fire spread, even when moisture contents are high. Others, like mineral content, may reduce intensity when moisture contents are low. High fuel loads in the fine fuel size classes with low fuel moisture contents and high volatile oil contents will contribute to rapid rates of spread and high fire line intensities, making initial attack and suppression difficult

2.1. Fuel particles and fuel bed characteristics

Fuel particles are the smallest elements considered to study fuel structure. They are pieces (dead or live) of the vegetation: such as branches, leaves, barks, cones, needles (Trabaud, 1974). It is at this level of the individual element that the physical, chemical and thermal properties of fuel particles are assessed. Description of the characteristics of fuel particles were conducted to facilitate the prediction of fire behaviour and to interpret the results of flammability experiments in the laboratory. This is due to the direct effect that these properties have on moisture relationships, heat transfer, ignition, and combustion; consequently, fuel particle characteristics contribute to the prediction of wildland fire intensity and severity.

Several characteristics required in the fire behaviour model show low variability and effects on fire behaviour, consequently they are usually kept constant in modeling (i.e. particle density, mineral content). Besides, other characteristics, such as the fuel moisture content, are critical to predict the potential for fire ignition and fire behaviour and can be assessed at multiple levels (particle, bed, complex). The organization of fuel particles into a microstructure, with defined proportion and configuration, can result in single or multiple *beds* or layers. Fuelbeds are described by several qualitative and quantitative physical and biological variables with emphasis on characteristics useful for fuels management and fire behaviour planning (Riccardi et al., 2006).

The following specific characteristics of *fuel particles* and *fuel beds* are considered in the fire behaviour modeling:

- Intrinsic (chemical composition, thermal properties, calorific content, density)
- Extrinsic (fuel load, size and shape, compactness, arrangement)
- Moisture content
- Structural composition

2.1.1. Intrinsic Properties

Fuel chemistry

The chemical characteristics strongly influence the combustion process and fire spread, but also affect the fuel heat content and the types of pollutants emanating from a fire. Plant material consists of polymeric organic compounds, generally described by the chemical formula $C_6H_9O_4$ (Byram, 1959), although it's clear that this generalized chemical formula varies, depending on fuel type, if grass or woody or material that is undergoing decay (Ward, 2001). Woody fuels are high in cellulose, lignin, and hemicellulose, while foliage and herbaceous fuels contain large amounts of readily combustible extractives.

Regardless, plant tissue is approximately 50% carbon, 44% oxygen, and 5% hydrogen by weight. Wood varies between 41% and 53% cellulose, which is the major constituent, between 15% and 25% hemicellulose, and between 16% and 33% lignin (23-33% of softwoods, and 16-25 % of hardwoods) (Browning, 1963). Cellulose is a polymer of glucose and is the main structural and chemical constituent of most plant tissue and fibers. The *cellulose* and hemicellulose make up the "whole carbohydrate fraction of wood." *Hemicellulose*s are polymeric units built of simple sugar molecules, in contrast to cellulose, which yield more than one type of sugar. The relative amounts of this sugar vary with species. *Lignin* is the chief non-carbohydrate constituent of wood and serves as a binding material in the intercellular layer. It is a polymer with a very large and complex macromolecular chemical structure.

Extractives in wood are constituents that can be removed by dissolving in such neutral solvents as water, alcohol, benzene and ether. Extractives include tannins and other polyphenolics, essential oils, fats, resins, waxes, gums, and starches. In quantity, they generally range up to about 10% depending on species and growth conditions. Oil and resins in the fuel increase the heat release because of their high energy content. Fuel containing concentrations of these chemical compounds would be expected to burn intensely (Whelan, 1995). On other hand, the leaves and wood (xylem) reduce flammability in some plant species. The range of fire intensities, rates of spread, and fire durations encountered in a particular ecosystem result in array of combustion conditions, which, in turn, result in a diversity of chemicals being emitted into the atmosphere by burning (DeBano et al., 1998).

Another important characteristic relative to fuel chemistry is the *total mineral content*, which is the fraction of a fuel mass composed of inorganic minerals (Philpot, 1968). The inorganic mineral content reduces the combustible fuel mass because only the organic portion of a fuel supports combustion. The total mineral content may also be referred as total ash content, usually comprising no more than about 0.1-3% of a woody substance. Calcium, potassium, phosphate, and silica are common constituents (Browning, 1963). They are usually uniformly distributed throughout the woody structure. The presence of active mineral content affects fire behaviour by interfering with the chemical processes of combustion; in effect, certain salts alter the pyrolysis process and promote the formation of char and tar at the expense of more flammable volatiles (Deeming et al., 1978).

Thermal properties

Thermal conductivity is a measure of the rate of heat flow through a material subjected to a temperature gradient. Thermal conductivity of wood is affected by density, moisture content, and extractive content. Heat content is the amount of heat that a unitary quantity of fuel oxidating releases. In woody fuels, on a dry weight basis, it is relatively consistent from one plant species to another (Deeming et al., 1978): every species has a definite calorific content, but the value for numerous species oscillates between 18000 and 19000 KJ/Kg.

Density

Particle density (weight per unit volume) is primarily an important fuel property because of its influence on thermal conductivity and consequent influence on time to ignition (Stockstad, 1967). Fuels with low density, for example, can be ignited in a shorter time for a given amount of heat, less than fuels with high density (Countryman, 1982): small experimental fires showed that the rate of spread decreased as the fuel density increased (Fons, 1946). The density of particles varies widely among species, and between foliage and wood, size of the material and its condition (alive or dead). Countryman and Philpot (1970) for instance reported that the density in *chamise* (chaparral dominated by

Adenostoma fasciculatum) was found to vary with the size of material and its condition (alive or dead), but over a relatively narrow range, and in another study, Countryman (1982) showed that the density of the living woody material was less than the foliage density, and that density increased with the size of material for the study species.

2.1.2. Extrinsic Properties

Fuel Load

The vegetation amount, or load, represents the component of phytomass that is material vegetable, alive and dead, that is placed over the mineral ground (Pyne et al., 1996). Thus *fuel loading* (total dry weight fuel per unit surface area) is also defined as a measure of the potential energy that might be released by a fire (Martin et al., 1979; Whelan, 1995; Pyne et al., 1996) the organic matter potentially involved in combustion. Fuel load is highly variable, with a broad range (in natural ecosystems, range from 0.5 to over 400 Mg ha^{-1}), linked with the vegetation species: lower fuel loads are found in herbaceous plants, while a high of fuel loads can be reached in a logging slash area. The readily combustible fuels are reduced the most by a prescribed fire, although substantial burning of the finer fuels and the litter layer can also occur. A wildfire can also be more erratic, leaving unburned, lightly burned, and severely burned areas in close proximity to each other (DeBano et al., 1998). Sites with low fuel loadings, which burn at low intensities, generally experience less severe impacts than those with larger fuel loadings, which burn at high intensities (DeBano et al., 1998).

Other conditions being equal, the amount of heat produced by a burning fuel bed will be strongly influenced by the amount of fuel available to burn (Countryman and Philpot, 1970). Fuel loading is commonly determined by assuming each shrub occupied a ground area equivalent to a circle with the diameter of the average crown diameter. The heat quantity produced from the combustion of a fuel layer is greatly influenced by the amount of the fuel available in the combustion process. The amount of the fuel can be express in various ways, according to the elements that are quantified. The term fuel load is used mainly for the surface fuel: this term represents the dry weight of the fuel for a given area, usually expressed in Mg ha^{-1}. In other cases, especially when referring to the fuel on the forest ground (i.e. the litter and the organic material in decomposition), depth in cm is used; while when the aerial fuel is quantified, beyond the biomass, bulk density is used. This term refers to the mass of particles per unit volume. Naturally, the volume includes the space between particles, and the spaces inside of the single particles holes.

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). Particle shape theoretically affects moisture exchange by means or differences in constants derived in the analytical solutions of the equation describing diffusion in the various particles. 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 load of fine fuels, the ignition of new fronts with spot fires is more frequent.

The size of the fuel particles is commonly defined by surface area to volume (SAV), which indicates the ratio σ between surface area and volume of a particle, and it is expressed in m^{-1} (m^2 m^{-3}). The smaller SAV ratio, the more voluminous fuel particles. The ratio of surface area to volume for various fuels is helpful in evaluations of their flammability. The ratio is a particularly meaningful measure of fuel particle size because of its relationship to rate of change of fuel temperature and moisture content.

For dead fuels, the moisture that is gained or lost must all go through the surface, so that the rate at which a fuel changes in moisture content is affected greatly by the amount of surface area in relation to the fuel volume. Not only the SAV ratio is meaningful regarding the moisture content, but also during combustion. A close relationship between SAV and some fire behaviour parameters exists: increasing this ratio in tightly packed fuels may decrease the spread rate and flame length. If an unburned piece of fuel is lit, heat is transferred to the fuel surface by all three methods of heat transfer–radiation, convection, and conduction. But the heat received by the surface is only transferred to the interior of the fuel by conduction, through the surface. Thus, the greater the surface area in relation to the fuel volume, the faster the fuel will be heated and burnt (Coutryman and Philpot, 1970). In thin fuel particles with a high surface-to-volume ratio, temperature and moisture content generally fluctuate more rapidly than in thick particles with a low surface-to-volume ratio (Fons, 1950; King and Linton, 1963). Additionally, studies developed in laboratories highlighted that the ignition time and the fire spread vary inversely as oppose to σ (Curry and Fons, 1938; Rothermel and Anderson, 1966).

Techniques for measuring surface area and volume were chosen to meet two requirements (Brown, 1970b). Both surface area and volume should be measured on the same fuel particle, and the volume should be determined for particles at low moisture content, 5 to 8 %, ovendry basis. Fine fuels are flammable at this range, which also is easy to maintain under laboratory conditions. For long narrow particles (needles, grasses and lichen) particle perimeter, cross sectional area, and particle length were measured on photomicrograph (Brown, 1970b), thus SAV is calculated with this formula:

$$\sigma = \frac{S}{V} = \frac{LP + 2A}{LA} = \frac{P}{A} + \frac{2}{L} \qquad (1)$$

where S is the surface area of particle (m^2), V is the volume of particle (m^3), L is the length of particle (m), P is the average perimeter of particle taken normal to length (m), and A is the average cross-sectional area of particle taken normal to length (m^2).

For particles having cylindrical shape the above equation simplifies to:

$$\sigma = \frac{4}{d} \qquad (2)$$

where d is the average diameter of particle (m). For leaves, the formula is:

$$\sigma = \frac{S}{V} = \frac{2Sa + tPa}{tSa} \qquad (3)$$

where Sa is the surface are on one side of leaf (m^2), t is the average thickness of leaf, and Pa is the perimeter of leaf outline (m) measured with a planimeter.

Compactness

The spacing of individual fuel elements in the fuel bed, or how crowded they are together may be referred in terms of *porosity*, or its converse, *compactness*. In a highly compact fuel bed the fuel elements are closely packed together, whereas in a less compact fuel bed the individual fuel elements are spaced far apart. A highly compact fuel bed has a low porosity value. The compactness is tied to fuel load and depth, as well to particle dimensions. Fuel bed compactness or porosity can be expressed in several ways. Fons (1946) used the ratio (λ) of the volume of voids in the fuel bed to the surface area of the fuel to measure porosity, but another convenient way to express fuel bed compactness is by the packing ratio (β) (Countryman and Philpot, 1970). This is defined as the ratio of fuel volume to fuel bed volume, in terms of effective volume occupied by fuel (Figure 4). The reciprocal (γ) of this ratio is the fuel bed porosity.

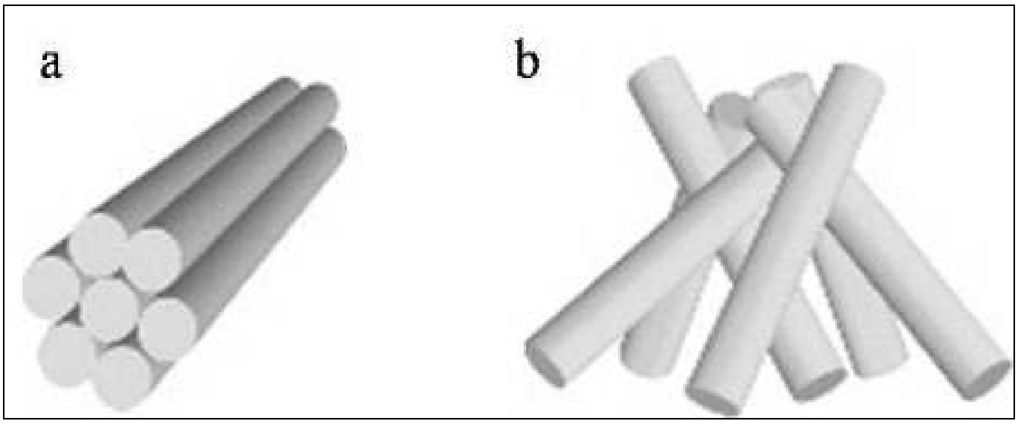


Figure 4. The packing ratio is the proportion of fuel in a unit volume of fuelbed. The same amount of fuel can be packed (a) tightly with only 10% air or (b) loosely with 90% air (from van Wagtendonk, 2006)

Several studies highlighted the relationship among compactness, packing ratio and fire behaviour. Burgan and Rothermel (1984) reported that a compact fuel bed burns slowly because airflow is impeded. On the other hand, a very open or porous fuel bed burns slowly because the individual fuel particles are spaced so far apart that there is little heat transfer between them: each particle in the fuel bed would burn as an individual. Fons (1946) correlated rate of spread of small experimental fires with the compactness. His work showed that rate of spread increased rapidly with decreasing compactness (increasing porosity). Rothermel and Anderson (1966) correlated rate of spread of small laboratory fires with the product of σ and λ. They found the spread rate increased rapidly as this product increased. By definition, the product of σ and λ is the ratio of fuel bed void volume to fuel volume—another means of expressing fuel bed porosity. However, in the data used in the correlation, σ as well as λ varied. Since rate of spread varies with both parameters, it is not clear from their published work how much of the change in spread rate was due to the surface-to-volume ratio of the fuel and how much to fuel bed porosity (Countryman and Philpot, 1970).

The *bulk density*, calculated as the weight per unit volume of fuel bed, and expressed with kg m^{-3}, is a convenient measure of fuel bed compactness (McCaw, 1991). For instance, in Rothermel's (1972) fire spread model, compactness is the fraction of fuel bed occupied by fuel and is calculated from the ratio of fuel bed bulk density to particle density. In modeling studies, additionally, particle density is usually regarded as a constant, thus fuel bed bulk density is the primary variable that determines compactness. Fuel bed bulk density is determined from estimates of fuel loading and fuel bed depth, which is an estimate of the vertical extent of the combustion zone (Brown, 1981), When the fuel is compact, it is common to observe 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. Horizontal continuity refers to the degree of change in physical characteristics of fuels over a given area. 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. The concept of arrangement is tightly linked with the fuel bed depth, which refers to an estimate of the vertical extent of the combustion zone (Brown, 1981).

2.1.3. Moisture content

The amount of fuel available for the combustion process is linked to the amount of water in the vegetation (fuel moisture) (Pyne et al., 1996). In order to ignite a fuel, it is necessary to induce water evaporation in the tissues. The heat that must be supplied to remove water from vegetation is proportional to the moisture content.

The fuel moisture content (FMC) is defined as the weight of water in the fuel, usually expressed as a percentage of the weight of ovendry fuel, and it is calculated as:

$$FMC = \frac{M_{wet} - M_{dry}}{M_{dry}} \quad (4)$$

where M_{wet} is the beginning weight, and M_{dry} the dry weight.

Moisture content in fuel is determined primarily by fuel type and the cumulative effects of past and present weather conditions (Nelson, 2001). The fuel moisture varies in space and in time, sometimes also rapidly and within a single fuel element: this effect unavoidably influences the fuel flammability (Biswell, 1989). The effects of fuel moisture on fire behaviour can be summarized in three principal components:

- increasing fuel preheating time (or ignition time);
- decreasing fuel consumption;
- increasing particle burning time, or *particle residence time* (Nelson, 2001).

Ignition time is related to the heat of ignition required to onset and complete volatilization of the fuel (Wilson, 1990). The heat of ignition is computed from the equation

$$Q_T = Q_f + MQ_M \quad (5)$$

where Q_T is the heat required to raise unit mass of dry fuel from ambient temperature to 400°C, Q_M is the energy to heat a unit mass of water to 100°C and then vaporize it, and M is the fractional moisture. Hence, it is logical that with increasing of M the amount of heat required to raise the temperature will also increase, and this entails increasing the preheating time.

The second effect of fuel moisture on the burning rate involves a decrease in fuel consumption due to the interaction among various fire behaviour characteristics (Nelson, 2001), such as available fuel loading and chemical composition. In effect, the available fuel loading, defined as the mass of fuel consumed per unit area depends on moisture content, flame temperature, and the mass of volatiles. The fuel chemical composition, on the other hand, and the thermal decomposition are two factors affecting the relative amounts of volatiles, which in turn determine the heat of combustion and the fraction of fuel available for flaming combustion (Albini, 1980; Susott, 1982).

In fine, the third effect of fuel moisture is an increase in the fuel particle residence time, generally understood as the time during which flame resides on individual particles in the fuel layer combustion zone. With experimental and theoretical studies, Albini and Reinhardt (1995) have shown that the characteristic particle burning time is proportional to Q_T. King (1973) in his study eventually explained that the demand for heat is satisfied by radiative and convective heat transfer within the combustion zone, and thus the moisture will increase the burning time by reducing radiation to the particles. To better understand how the moisture content affects the fire behaviour, one must consider live and dead fuel separately, within these broad categories, the single particles or a collection of particles making a fuel complex. In many cases, a fuel complex is composed of a mix of live and dead particles from various fuel types whose moisture content may vary over a wide range.

The dead fuel moisture influenced by all the components forming the fire environment triangle (weather, fuel and topography), but the most important elements are fuel composition (needles, bark, leaves, etc.) and size, as well as location. The equilibrium moisture content (EMC) is a useful characteristics to express the dead fuel moisture, and it represents the constant value of M attained by dead forest fuel when they are exposed for an extended period in air of constant relative humidity and temperature and in which changes due to variability in wind, solar radiation, and barometric pressure are small (Nelson, 2001).

The size classes that are traditionally used to categorize dead fuels correspond to fuel moisture timelag classes (Deeming et al. 1977). 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 (Lancaster, 1970). 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: less 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 3).

Table 3. Dead fuel timelag and diameter class (Deeming et al., 1977)

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

Differentiated by the dead fuel moisture, and linked with meteorological conditions, the biomass presents seasonal variations in moisture connected with physiological and phonological processes of plants. As referred by Nelson (2001) "*the instantaneous level of moisture content in forest fuel is strongly influenced by the internal structure of the material*". 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 sensitive to short periods and seasonal meteorological conditions.

2.1.4. Structural composition

Forest fuels are compounds of different particle sizes of live and dead vegetal matter, arranged in complexes with different components, named layers. Because forest fires are usually categorized according to the location of the uppermost fuel stratum through which they burn (ground, surface, or crown fires), the fuel classification trace out the same strata. Hence fuels may be classified as ground fuels, surface fuels, or crown fuels (Figure 5).

Ground fuels consist of the highly decomposed organic material in contact with the inorganic layer and include duff, roots, peat, and rotten wood or bark coming from downed twig and branches (Pyne et al., 1996; Nelson, 2001). In moist climates, fuel above the mineral soil has three components: the litter layer, the partially decomposed fermentation layer, and the well-decomposed humus layer. Several authors refer to duff as all material above the upper surface of the mineral soil (Stocks, 1970), but usually a clear distinction is made between litter and duff: the first term refers to the litter and fermentation layers, where it is still possible to recognize the material type and the species to which it belongs; the second refers to the humus layer, within decomposed material in which the original structure is no longer discernible, typically bounded by fungal mycelium.

Surface fuels represent the more studied fuelbed layer, since most fires originate and propagate in this component (Pyne et al., 1996). This layer typically include dead material on the ground (recently fallen and partially decomposed tree leaves, fallen twigs, bark and branches) as well as live or dead grasses, forbs and shrubs less than 1.8 m tall (Davis, 1959). 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.

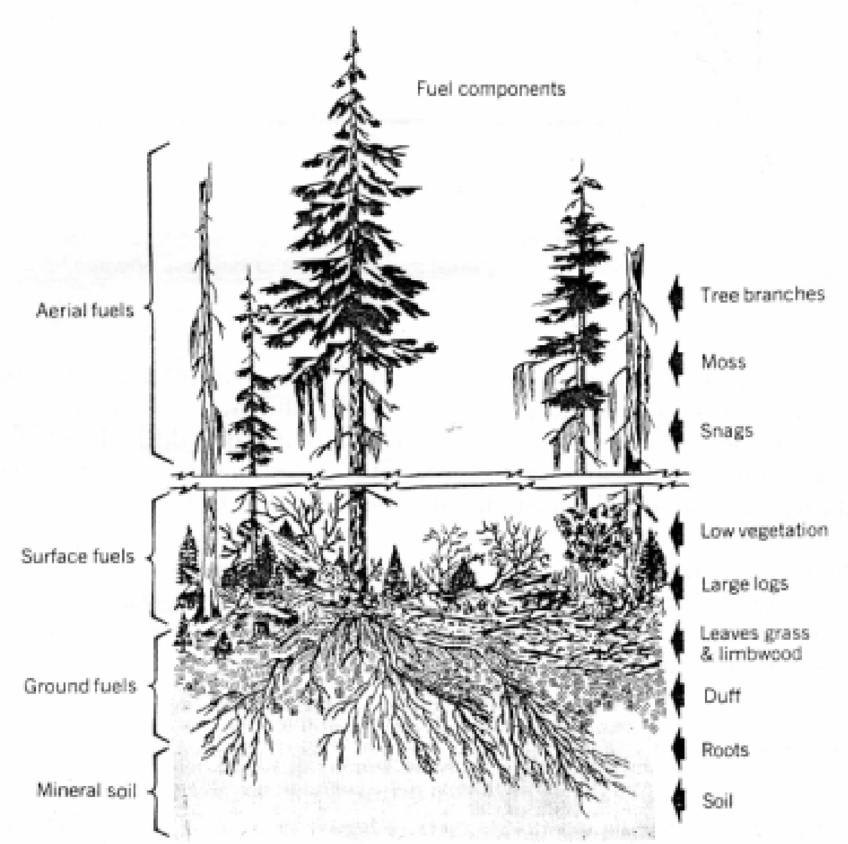


Figure 5. Fuel structural composition (from Barrow, 1951)

Canopy fuels, or *aerial*, include tree crowns and shrubs with heights over 2 m (Pyne et al., 1996). The aerial vegetation is largely composed of biomass, with high moisture content: therefore the crown burns only if the heat released by the fire is maintained for a long time or if the flames directly burn the crowns. In order for the flames to arrive in the canopy, the presence of a layer of shrubs and small trees is necessary, which eliminates the gap between surface and aerial layer. The canopies of deciduous species also are crown fuels and have higher moisture content than conifers. Exceptions occur under dry, windy conditions and when the fuels contain highly volatile and flammable substances.

3. FUEL CLASSIFICATION

As depicted in the previous paragraph, the fuel particle organization constitutes a single or multiple beds or layers, which aggregated may result in a fuel complex. Further increasing the complexity scale, when the spatial distribution of all layers is considered, this macrostructure is defined "fuel type" or "vegetation type", with given vertical and horizontal fuel distribution properties (EUFIRELAB, 2007). There is infinite variability in fuels in a natural ecosystem. Sandberg and others (2001) assert that it would be prohibitively difficult to inventory all fuelbed characteristics each time that it is necessary to predict events or to make management decisions because of the natural structure of the fuel complex: it varies widely in its physical attributes, and in its potential fire behaviour and also effects the options it presents for fire control and use.

Therefore, the need to classify fuels for management purpose evolved as a consequence (Brown and Davis, 1973; Martin et al., 1979; Pyne et al., 1996). Fuel complexes can be classified in a number of ways according to their composition, structural arrangement, position, role in fire behaviour, and general fire behaviour characteristics, inferring fuel complex properties from limited observations, simplifying the complexity to a reasonable degree (Sandberg, 2001).

According to the deliverable EUFIRELAB D-02-06 (2007), it is possible to recognize essentially four methodologies to characterize and describe the fuel complex:

- Direct evaluation
- Fuel stratification
- Qualitative description
- Fuel model

Fuel classification can also be based on the fuel state (DeBano et al., 1998) that is the moisture condition of the fuels, which largely determines the amount of fuel available for burning at a given time (Martin et al., 1979; Bond and van Wilgen, 1996). One approach to classifying fuels relative to their state is based on the time it takes for the moisture content of the fuel in question to adjust to changes in environmental conditions (i.e. timelag, see 2.2.3). Fuel classification based on fuel state includes:

- Timelag constant, the time for a fuel's moisture content to lose 63% of the difference between its moisture content at the beginning of the time period and the new equilibrium moisture content in the conditions to which it is exposed (Fosberg, 1970; Pyne et al., 1996);
- Timelag interval, the time required for dead fuel to lose 63% of this difference;
- Timelag classes, that are used to partition dead fuels in the national Fire Danger Rating System categories used in the NFDR of the USDA Forest Service (Martin et al, 1979; Pyne et al., 1996): live fuels – grouped by category as wood or herbaceous fuels; dead fuels – grouped by size class as 1, 10, 100, or 1000 hour timelag classes.

Table 4. Timelag Class, Timelag Interval, and Fuel Dimensions and Type (Martin et al., 1979)

		Fuel Dimension (cm)	
Timelag Class	*Timelag Interval (h)*	*Roundwood*	*Litter and Duff*
1 h	0-2	< 0.6	Surface
10 h	2-20	0.6 - 2.5	surface - 2
100 h	20-200	2.5 - 7.5	> 2 - 10
> 100 or 1000 h	>200 or 2000	> 7.5	

Fahnestock (1970), in his guide "Two keys for appraising forest fire fuels", was among the first to use the concepts of *timelag* class. Fahnestock describe physical fuel properties in terms of fine, small, medium size classes and sparse, open, dense, fluffy, or thatched for compactness or a combination of loading and depth, and interpreted the size class descriptions for each fuel stratum according to the physical dimensions and timelags associated with the 1964 NFDR (USDA, 1964).

3.1. Direct evaluation

The fuel classification system is a subjective estimate executed by a specialist that has extensive experience on wildfires happened in landscapes similar to that one under investigation (Chandler, 1979). The first efforts on classifying fuels, rather than focusing on the fuel types from a vegetation or fuel loading point of view, have been on rating the potential rate of spread or rate of perimeter increase from an initiating fire so that initial attack response time could be designed to contain the fire at a reasonable size (Sandberg, 2001). For instance, Show and Kotok (1930) used the concept of 'hour control zones' to classify vegetation cover types according to the velocity of the initial attack, after the fire is started, in order to obtain an acceptable probability of control. Later, the consideration in classifying fuels was "how difficult a potential fire would be to suppress". This approach was carried out by Hornby (1936), who classified fuels both by their potential rate of spread and the resistance to control under average worst burning conditions, typical of the worse part of the fire season. Hornby formalized the fuel classification into categories, based on rate of spread and resistance to control into classes of low, medium, high, and extreme. For example, for the Northern Rocky Mountains, MT (USA), the standard fuel types described by Hornby were:

1. Brush—grass
2. Ponderosa pine
3. Larch—fir
4. Douglas-fir and lodgepole pine
5. White pine and lodgepole pine
6. Subalpine fir
7. White fir and spruce

Rate of spread was estimated by statistical analysis of individual fire reports, and resistance to control was estimated by measuring the amount of time needed to construct a fireline. The problem of this system is that the behaviour of fire for a defined vegetation type in normal meteorological conditions can be completely different from situations of extreme or with low risk conditions. Besides, it considers the 'resistance to control' approach tied only to handline construction, and therefore limited to an initiating fire, and not other severe fire behaviour. Although this method has been adapted (Jemison and Keetch, 1942; Barrow, 1951) and modified (Brown and Davis, 1973), it has been the official fuel classification system in USA until about 1970.

3.2. Fuel stratification

Another of the first methodologies developed in order to categorize the fuel complex was the fuel stratification. In particular, the vegetation is classified by considering the position of its elements with respect to a vertical plan (Pyne et al., 1996): classical schemes of fuel stratification emphasize surface fuels, given their role in fire propagation. The 'surface fuel' concept is widely variable among authors and countries thus different stratification systems were adopted by countries.

In Australia, for example, the major attempt is to describe fuel complexes that are associated with particular vegetation types, thus the principal factor accounted for, is the continuity in the horizontal and vertical dimension (McCaw, 1991). The extent and pattern of discontinuity is important as it has bearing on the threshold limits at which fire will spread in different fuel beds. Fuel is classically stratified (Table 5) into ground layer, comprising peat and duff, litter composed by dead leaves, moss, lichen, prostrated herbs, grounded logs, elevated, including tall herbs, grasses, forbs, shrubs, dead twigs, logging or pruning slash, ladder constituted by bark, resin, moss and liken, and in fine canopy with foliage and dead trees.

In the USA several authors proposed the Fuel Condition Class (FCC) (Shaaf, 1996; Ottmar et al., 1998), designed to improve fuel load assignments to account for additional fuelbed characteristics within six strata including tree, shrubs, grasses, woody surface fuels, litter, and duff. Table 6 illustrates the classification framework on which this system is based on.

Table 5. Scheme adopted by the Australian Forestry Council Working Group on Fire Management (adapted from McCaw, 1991)

Fuel Element	*Example*
Ground	Peat, Duff
Litter	Dead leaf litter Moss, lichen, prostrate herbs Grounded logs
Elevated	Tall herbs Grasses Hummock grasses Bracken Woody shrubs Dead twigs Logging or pruning slash
Ladder	Bark -firmly attached to stem -in loose ribbons -in loose ribbons Resin Moss and lichen
Canopy	Foliage Stag trees

Table 6. FCC System Classification frame work

vegetation type	ponderosa pine, mixed conifer, lodgepole pine, western juniper, sagebrush, and grass
age category	bare ground, immature, and over mature
load category	low, medium, and high
activity category	none, pre-commercial thinning, commercial thinning, pile, lop and scatter, crush, and yard unmerchantable material

In spite of the 192 fuelbeds contained in the FCC system, populated with fuel input data from scientific literature, large databases, and expert knowledge, one of the major weaknesses is the presence of a limited number of fuelbeds, generally representing the Pacific Northwest area, a limited list of fuelbed categories representing each fuelbed, and no possibility to customize an FCC fuelbed (Ottmar et al., 1998).

Later, the Fuel Condition Class was modified by Sandberg et al. (2001), and it was identified with new name of Fuel Classification Class System (FCCS). In this new system the first purpose was to modify the classification and characterization scheme with the aim of infer on fuelbed properties from limited observation, and to simplify the complexity to a reasonable degree, but to not oversimplify the description of wildland fuelbed (Sandberg et al., 2001). Therefore, the original fuel complex scheme was maintained (Figure 6), which subdivides vegetation in six horizontal fuelbed layers, complex in structure, and diverse in their physical attributes and the biological origin of their components. Every fuelbed layer represents unique combustion environments, and is broken into one or more fuel types, with common combustion characteristics, called fuelbed categories. Each category is described by physiognomic, capturing qualitative features of the category, and gradient variables, relative to the abundance of fuel.

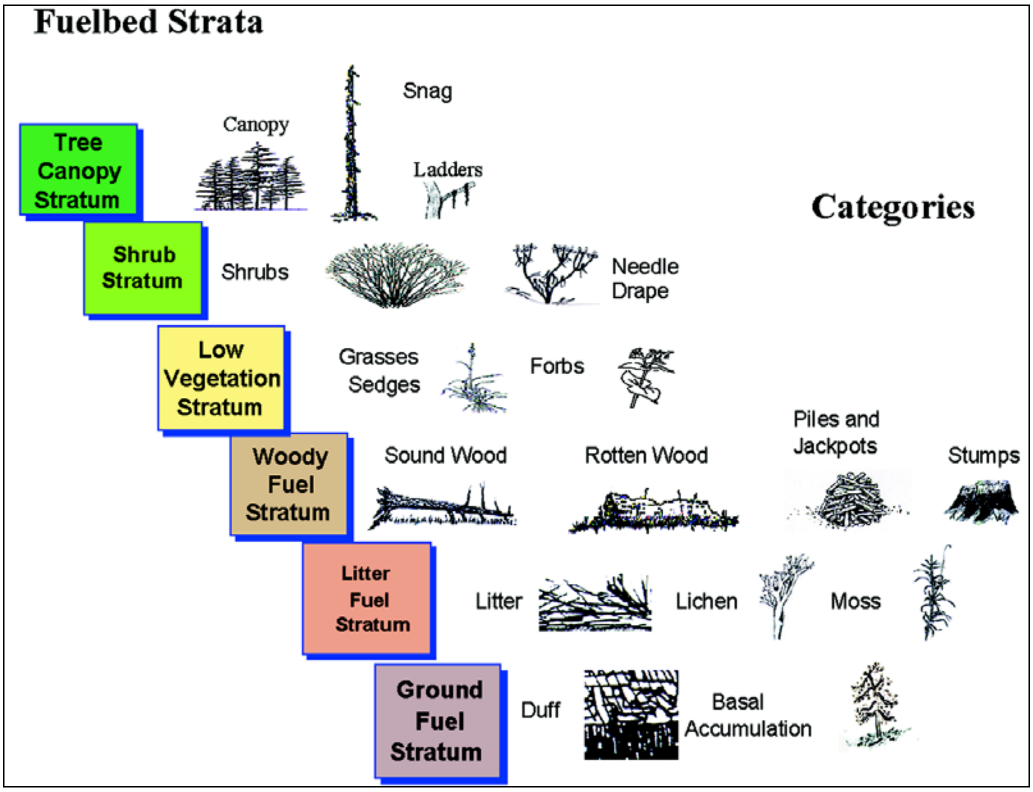


Figure 6. Fuel bed strata and categories in the Fuel Classification System (http://www.fs.fed.us/pnw/fera/jfsp/fcc/)

On the other hand, the System objectives were extended and broaden, since it was no longer a simple classification scheme, but also a model that stratifies fuelbeds into six horizontal fuelbed strata that represent unique combustion environments.

In Europe, one of the first efforts to classify fuel in Europe was conducted in Greece, with the development of the "PROMETHEUS" system (Prometheus Project, 1999), which deals with the composition and the sorting of various types of vegetation within the ecosystems of Greek forests. According to this system, fuels are divided into 7 types (Giakoumakis, 2002). The various types of forest fuels are as follows:

– Land Fuel: This category comprises lands consisting of agricultural and herbaceous vegetation. Such fuel is usually thin and dry during the summer period, and consequently fires spread quickly and at a low flame height.
– Low-lying Shrubs: This category comprises grasslands, low-lying shrubs (30-60-cm high) and a high percentage (30-40%) of herbs. This category also includes harvested forest areas in which some residual trees still may exist.

- Medium Shrubs: This category comprises medium to large-sized shrubs (0.60-2.0-m high). Land coverage can be greater than 50%. Areas of natural or artificial regeneration can also be included in this type.
- Tall Shrubs: This category comprises tall shrubs (>2.0-m high) and areas consisting of young tree plantations, resulting from regeneration efforts.
- Forest areas with no understory: This category comprises areas where undergrowth has purposely been removed, either by mechanical or chemical methods. In this category, fires are usually slow spreading.
- Forest areas with medium understory: This category comprises forests where the tree crown is much higher than the uppermost parts of the understory vegetation (i.e., there is a break between the fuels found in the understory and the crown). The understory usually consists of low-lying shrubs. Fires characteristic of this category are usually low intensity, which can sometimes develop into higher-intensity fires under extreme climate conditions.
- Forest areas with high and dense understory: This category comprises forests with high and dense understory growth where there is little separation between the tree crowns and the understory (i.e., continuous fuels). The understory fuels act as ladder fuels to allow the fire to crown in this fuel type, which favors severe and high-intensity fires.

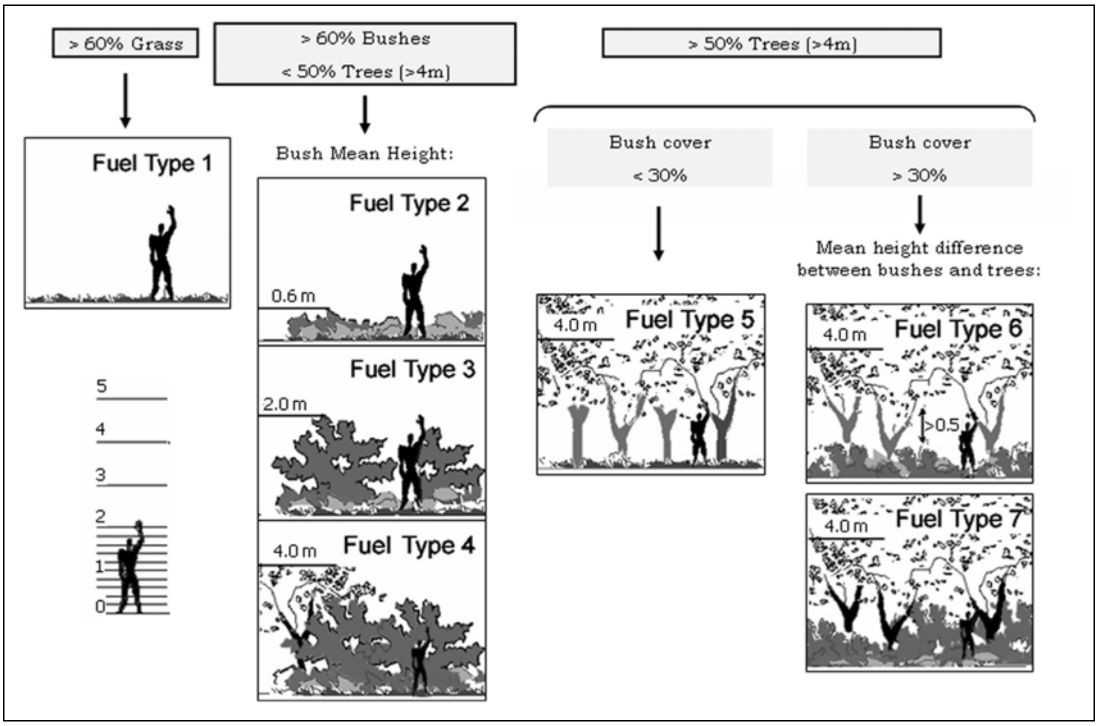


Figure 7. Prometheus fuel classification system for Mediterranean systems (from Arroyo et al., 2006)

3.3. Qualitative fuel descriptions

A few examples exist of fuel classification based on qualitative description, and those are mainly from the Australian and Canadian fire experiences. In those countries, the fuel is described as 'fuel type': an identifiable association of fuel elements of distinctive species, form, size, arrangements, or other characteristics that will cause a predictable rate of spread or resistance to control under specific weather conditions (Food and Agriculture Organization of the United Nations, 1986; National Wildfire Coordinating Group, 1996; Canadian interagency Forest Fire, 2002). Moreover, a fuel type is a fuel complex with sufficient homogeneity and extending over an area of sufficient size, so its equilibrium fire behaviour can be maintained (Forestry Canada Fire Danger Group, 1992). According with the above definition, often a fuel type is used in conjunction with forest fire danger rating systems, as the primary input of fire behaviour models.

In Australia, fuel types were developed exclusively for the Fire Danger Rating Systems, and they are open grasslands, dry eucalyptus forest and heat/shrublands. The forecasting of fire danger ratings is kept separate from the predictions of fire spread and fire behaviour in these fuel types (Cheney, 1992).
The McArthur Forest Fire Danger Meter (McArthur, 1997) was designed for general forecasting purposes and is based on the expected equilibrium behaviour of fires burning in high eucalypt forest and traveling over level to undulating topography. The Grassland Fire Danger Meter predicts a fire's potential rate of forward spread across continuous grass in gently undulating terrain. Moreover, McCarthy (1998) also proposes a guide to assess fuel hazard, defined as the fire suppression difficulty that pertains to a given level of fire behaviour: each fuel condition class is essentially described in qualitative and physiognomic terms.

In Canada, the current form of the Canadian Forest Fire Danger Rating System (CFFDRS) is made up of two major subsystems that have been formally documented and disseminated. These systems, the Canadian Forest Fire Weather

Index System (Canadian Forest Service, 1987) and the Canadian Forest Fire Behaviour Prediction System (Forestry Canada Fire Danger Group, 1992), have been used operationally throughout all of Canada for many years. The FBP System organizes fuels into five major groups (Table 7) with a total of 16 discrete fuel types altogether recognized (Forestry Canada Fire Danger Group, 1992). These fuel types are used to describe fire behaviour characteristics that would be expected under various burning conditions. Fuel types in the FBP System are described qualitatively, rather than quantitatively, using descriptive terms on stand structure and composition, surface and ladder fuels, and the specific forest floor covered and organic layer are presented.

Table 7. Fuel types of the Canadian Forest Fire Behaviour Prediction System

Group	*Descriptive name*
Coniferous	C1: Spruce lichen woodland
	C2: Boreal spruce
	C3: Mature jack or lodgepole pine
	C4: Immature jack or lodgepole pine
	C5: Red and white plantation
	C7: Ponderosa pine-Douglas fir
Decidous	D1: Leafless aspen
Mixedwood	M1: Borel mixedwood leafless
	M2: Boreal mixedwood green
	M3: Dead balsam fir mixedwood leafless
	M4: Dead balsam fir mixedwood green
Slash	S1: Jack or lodgepole pine slash
	S2: White spruce-balsam slash
	S3: Coastal cedar-hemlock Douglas fir slash
Open	O1:Grass

3.4. Fuel models

In the 1972, Rothermel redefined the ratio of energy released to the adjacent fuels from the burning front (that could not be solved analytically), in new terms that allowed for a mathematical approximation, and then tested the model using known variables in a wind tunnel/combustion chamber. His semi-empirical model is thus developed essentially from results obtained from a 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 development of a mathematical spread model allowed consideration of the intensity and rate of spread of initiating fires in homogeneous fuels, modernizing fire behaviour prediction systems, and requiring a particular fuel description.

In addition, Rothermel's model quickly became the most widely used method to predict fire behaviour, and remains so today (Sandberg et al., 2001), in spite of the broad range of fire simulators realized in the last decades. In the field of fuel description, thus, the availability of the spread model greatly increased the demand for quantitative fuels data, namely the development of *fuel models* and the relatives *photo series*.

Rothermel himself defined the term "fuel model", as a complete set of inputs concerning the fuel necessary for the fire spread mathematical model application. Subsequently, Deeming (1975) specified that it was a mathematical description of the superficial fuels, to which are associated several necessary variables in order to calculate the main characteristics of the fire behaviour. The Food and Agriculture Organization of the United Nations (FAO) in the 1986 defined fuel model as "the simulated fuel complex for which all fuel descriptors required for the solution of a mathematical rate of spread model have been specified". In any case, the creation of a fuel model has the advantage of representing all the types of vegetation whose characteristics are similar to those described from the model.

A common characteristic of the fuel model is the interpretation of the size class descriptions for each fuel stratum according to the physical dimensions and timelags associated with the 1964 National Fire Danger Rating System (NFDR) (USDA, 1964): within each fuel model, the load was distributed by size or timelag classes, correlated with groupings of foliage and twigs, branchwood, and tree or shrub material.

3.4.1. Fuel modeling in the United States

Pioneers in the fire behaviour studies, the United States also developed and produced numerous methodologies for the analysis of the vegetation, finalized to the creation of fuel models.

In fact, the Rothermel mathematical model for fire spread has been incorporated into the NFDR and the BEHAVE group of fire prediction programs. Although the NFDR and BEHAVE use the same mathematical model, the uses of the two programs differ significantly due to different target applications and different weightings of parameters within the model. For example, the two systems differ remarkably in the construction of fuel models, distinguishing the fire behaviour fuel model for the fire prediction program as BEHAVE, and fire danger rating fuel model for the NFDR.

Fire behaviour fuel model

Rothermel (1972) documented the initial eleven fuel models relative to the main vegetational types, founded in the areas in which the mathematical model has been modified, mainly for the northern American forest. The fire behaviour fuel model describes the fine fuel that carries fire spread, as required by Rothermel's model as it is applied to fire behaviour prediction. The models were conceived of as a set of standardized and stylized inputs for use in the spread model across the range of fire behaviour commonly seen in surface fuels. Stylized fuel models were meant to approximately represent fuelbed properties found in nature.

Albini (1976) refined those 11 fuel models and added two others. His tabulated set became what is now called 'the original 13 fire behaviour fuel models' (Table 8). The 13 fuel models were developed to provide standardized numerical fuelbed descriptions in order to generate reasonable and accurate fire behaviour predictions using the spread model. Each fuel model is a small database of about 30 fuelbed properties that determine its fire behaviour potential, described mainly by:

- The fuel load and the ratio of surface area to volume for each size class;
- The depth of the fuel bed involved in the fire front;
- The fuel moisture, including that at which fire will not spread, called the moisture of extinction.

The descriptions of the fuel models include also the total fuel load less than 7.5 cm, dead fuel load less than 0.6 cm, live fuel load of less than 0.6 cm, and herbaceous material and fuel depth used to compute the fire behaviour values given in the nomographs.

One advantage is that limiting the number of stylized fuel models to 13, has made them easy to share, to visualize and to communicate within the fire community. Besides, their significant value is in the quality of fire behaviour predictions that result from their use. On the other hand, it must to take into account that the standard 13 models include only the inputs required to the Rothermel's (1972) model: forest floor depth or load or any measure of large woody fuels are not considered, for example. Eventually they were not designed to be correlated with actual fuel loadings, vegetation cover, remote-sensing signatures, or modeled ecosystem dynamics, thus the assignment of fuel loadings across the landscape is not robust enough, and large errors can be expected from such estimates (Sandberg, 2001).

Table 8. Description of fuel models used in fire behaviour as documented by Albini (1976)

Fuel model	*Typical fuel complex*	*fuel loading*				*Fuel bed depth*	*Moisture of extinction dead fuels*
		1 hr	*10 hr*	*100 hr*	*Live*		
		-----------Tons/ha-----------				m	%
	Grass and grass-dominated						
1	Short grass (0.3 m)	1.83	0.00	0.00	0.00	0.30	12
2	Timber (grass and understory)	4.94	2.47	1.24	1.24	0.30	15
3	Tall grass (0.80 m)	7.44	0.00	0.00	0.00	0.76	25
	Chaparral and shrub fields						
4	Chaparral (1.8 m)	12.38	9.91	4.94	12.38	1.83	20
5	Brush (0.6 m)	2.47	1.24	0.00	4.94	0.06	20
6	Dormant brush, harwood slash	3.71	6.18	4.94	0.00	0.76	25
7	Southern rough	2.79	4.62	3.71	0.91	0.76	40
	Timber litter						
8	Closed timber litter	3.71	2.47	6.18	0.00	0.06	30
9	Hardwood litter	7.22	101.31	0.37	0.00	0.06	25
10	Timber (litter and understory)	7.44	4.94	12.38	4.94	0.30	25
	Slash						
11	Light logging slash	3.71	11.14	13.62	0.00	0.30	15
12	Medium logging slash	9.91	34.67	40.85	0.00	0.70	20
13	Heavy logging slash	17.32	56.93	69.31	0.00	0.91	25

Fire danger rating fuel model

The National Fire Danger Rating System (NFDRS) of the United States was released for general use by agencies throughout the United States in 1972, with modified versions released in 1978 and 1988 (Andrews et al., 2003). The current system is based on the physics of combustion and laboratory developed constants and coefficients reflecting the relationships between various fuels, weather, topography, and risk conditions.

In the 1972 NFDRS, 9 models were provided (Deeming et al., 1972), but in a second time, the number of fuel models increased to supposedly improve resolution and representativeness, with the result of an array of 20 models (Deeming et al., 1977): eight of the nine 1972 NFDRS fuel models were retained, and twelve totally new models were developed (Deeming et al., 1977).

Fuel model types were selected for modeling based on:

– Significance as a fire type;
– Interest expressed by fire managers;
– The availability of fuels and fire behaviour data with which to develop and test the fuel models (Deeming et al., 1977).

Some of the fuel types matched the assumptions of uniformity, continuity, and uniform distribution of size classes very well, and enough data existed for straightforward modeling. These fuels include the grass models, slash models, and the needle litter of southern plantations, western pine, and short needled conifers. In contrast, when no concrete data was available, "best guesses" were used to build the fuel models. The model's predictions were eventually compared to fire behaviour observations, or if none were available, the results were subjectively evaluated by the researchers. Once a preliminary set of fuel models had been developed, the fire danger estimates produced using these models were evaluated by fire managers. The evaluation included the rate of spread and flame length prediction, and the seasonal profile of the NFDRS indexes, components, and live fuel moistures.

Table 9. Description of the 20 models in the 1978 NFDRS (Deeming et al., 1977)

Fuel model	*General description*	*Fuel model*	*General description*
A	wester annual grasses	K	light logging slash
B	california mixed chaparral	L	western perennial grass
C	pine grass savanna	N	sawgrass
D	southern rough	O	high pocosin
E	hardwoods (winter)	P	southern pine plantation
F	intermediate brush	Q	alaskan black spruce
G	short needle pine (heavy dead)	R	hardwoods (summer)
H	short needle pine (normal dead)	S	tundra
I	heavy logging slash	T	sagebush-grass
J	intermediate logging slash	U	western long-needled conifer

Anderson (1982) cross-referenced the 13 fire behaviour fuel models with the 20 fuel models of the NFDRS by means of a similarity chart (Table 10), which are presented in 4 fuel groups: grasslands, shrublands, timber, and slash. Each group comprises three or more fuel models.

The fuel models showed in Table 10 were assigned according to the fuel layer controlling the rate of fire spread. Some second and third choices are indicated for situations where fire spread may be governed by two or more fuel layers, depending on distribution and moisture content. A criterion for choosing a specific fuel model is that the model represents the best conditions of fire burns in the fuel stratum. This means that there will be situations where one fuel model better represents the rate of spread while another fuel model may better depict fireline intensity (Byram, 1959).

Table 10. Similarity chart to align physical descriptions of fire danger rating fuel models with fire behaviour fuel models (Anderson, 1982)

NFDRS FIRE BEHAVIOUR FUEL MODELS		*FUEL MODELS* 1	2	3	4	5	6	7	8	9	10	11	12	13	
A	wester annual grasses	X													GRASS
L	western perennial grass	X													GRASS
S	tundra	X					3rd			2nd					GRASS
C	pine grass savanna		X							2nd					GRASS
T	sagebush-grass		X			3rd	2nd								GRASS
N	sawgrass			X											GRASS
B	california mixed chaparral				X										SHRUB
O	high pocosin				X										SHRUB
F	intermediate brush					2nd	X								SHRUB
Q	alaskan black spruce						X	2nd							SHRUB
D	southern rough						2nd	X							SHRUB
H	short needle pine (normal dead)								X						TIMBER
R	hardwoods (summer)								X						TIMBER
U	western long-needled conifer									X					TIMBER
P	southern pine plantation									X					TIMBER
E	hardwoods (winter)									X					TIMBER
G	short needle pine (heavy dead)										X				TIMBER
K	light logging slash											X			SLASH
J	intermediate logging slash												X		SLASH
I	heavy logging slash													X	SLASH
		GRASS			SHRUB				TIMBER			SLASH			

Scott and Burgan (2005) fire behaviour fuel models

Anderson (1982) highlighted that the original 13 fire behaviour fuel models are mostly used during the "severe periods of the fire season when wildfires pose greater control problem", to predicting spread rate and intensity of active fires. This is in part because the associated dry conditions lead to a more uniform fuel complex, an important assumption of the underlying fire spread model (Rothermel, 1972). However, they are insufficient for other purposes, including prescribed fire, wildland fire use, simulating the effects of fuel treatments on potential fire behaviour, and simulating transition to crown fire using crown fire initiation models (Scott and Burgan, 2005). Therefore, Scott and Burgan (2005) defined a new set of 40 fire behaviour fuel models with the intent to:

– *"improve the accuracy of fire behaviour predictions outside of the severe period of fire season, such as prescribed fire and fire use application*;
– *increase the number of fuel model applicable in high-humidity areas*;
– *increase the number of fuel models for forest litter and litter with grass or shrub understory*;
– *increase the ability to simulate changes in fire behaviour as a result of fuel treatment by offering more fuel model choices, especially in timber-dominated fuelbeds*".

Fuel models in the new set are grouped by fire-carrying fuel type, and are summarized in Table 11.

Table 11. Fire carrying fuel type (Scott and Burgan, 2005)

Fuel type	*General description*
NB	Nonburnable
GR	Grass
GS	Grass-Shrub
SH	Shrub
TU	Timber-Understory
TL	Timber Litter
SB	Slash-Blowdown

There are several unique characteristic originalities in this new set of fire behaviour fuel models. First and foremost, the documentation and naming of the new fuel models refer to fuel or fuel type, not vegetation or vegetation types. For example, what was formerly termed a "Chaparral" fuel model might now be called a "heavy Load, tall Brush" model because one fuel model can be applied to many vegetation types (Scott and Burgan, 2005).

Secondly, all fuel models with an herbaceous component are dynamic: that is, in the live herbaceous component load is transferred to dead load as a function of its moisture content. Therefore, the dynamic fuel model process, as described by

Burgan (1979), takes into consideration the live herbaceous moisture contents: according to the amount of herbaceous fuel considered live or dead (Table 12).

Table 12. The dynamic fuel model process (from Scott and Burgan, 2005)

Moisture content percent	*Type*	*Category*
> 120	herbaceous fuels are green	live
30 - 120		½ dead
< 30	herbaceous fuels considered fully cured	dead

Thirdly, to facilitate standard comparisons of the new fire behaviour fuel models with the original 13 fuel models and with each other, Scott and Burgan developed standard dead and live fuel moisture scenarios (Table 13). There are 16 unique moisture scenario combinations.

Table 13. Dead and Live fuel moisture content values (percent) for the dead and live fuel moisture scenarios (from Scott and Burgan, 2005)

	D1 Very low	D2 Low	D3 Moderate	D4 High
1 hr	3	6	9	12
10 hr	4	7	10	13
100 hr	5	8	11	14

	L1 *Fully cured* Very low	L2 *Two-thirds cured* Low	L3 *One-third cured* Moderate	L4 *Fully green (uncured)* High
Live herbaceous	30	60	90	120
Live woody	60	90	120	150

3.4.2. Fuel modeling in Europe

In Europe, several attempts were conducted to characterize fuelbeds and develop fuel models, but these efforts are primarily applicable to a few countries, to describe local condition, usually for fuel hazard mapping or for research purposes, namely to investigate the effects of fuel management activities (Fernandes et al., 2006). In Portugal, for example, several studies have been completed, and other research is underway. Cruz (2005) developed a photographic guide of the principal fuel complexes in Central Portugal, based on the fuel identification and characterization with the aim to assemble the fuel models. The fuel models are summarized in Table 14.

Fernandes and colleagues (2006), instead, translated a forest classification based on the Portuguese National Forest Inventory (NFI) into fuel models (Table 14). The NFI includes variables that describe the vertical structure and composition of Portuguese mainland forests on 2258 sampling plot (DGF, 2001). The NFI field assessments were aimed at describing forest composition and vertical structure consisted of percentage cover estimates by species or groups of analogous species per height class. A previous study (Godinho-Ferreira et al., 2005) analyzed the NFI database and identified 10 main forest types and 22 structural types. The fuel modeling process consisted of the estimation of fuel parameters for each forest type (omitting the shrub dominated cover types, since the main interest was to assess fire hazard in forested ecosystems) (Fernandes et al., 2006) and development of a fuel model for each structural forest type on Behave Plus 3.0 (Andrews et al., 2003).

Differently, in Greece, Mediterranean vegetation types were subject to study. They cover approximately 39% of the total surface and are subjected, on average, to 78% of the total numbers of fires and 85% of the total area actually burned (Dimitrakopoulos, 1993). Mediterranean vegetation type were classified into typical fuel models by measuring the classical parameters in 181 representative natural fuel complexes. The data set was statistically analyzed by a two stage clustering procedure that produced seven distinct fuel models (Dimitrakopoulos, 2002) (Table 16). The indicative range of potential fire behaviour for every fuel model was calculated with the Behave fire behaviour prediction system, using as inputs the specific fuel parameter values of every model.

Table 14. Fuel models for Central Portugal (Cruz, 2005)

Fuel type	*General description*	*Fuel Model*	*Fuel type*	*General description*	*Fuel Model*
Grass		HER-01	Eucalyptus stand	Young (less than three years old)	EUC-01
Decidous stand		FOLC-01	Eucalyptus stand	Without shrub undestory	EUC-02
Exploitation debris	Woody debris due to exploitation or silvicoltural treatments	RESE-01	Eucalyptus stand	With shrub undestory	EUC-03
Conifer stands	Young, dense,without silvicoltural treatments	PPIN-02	Eucalyptus stand	With woody debris	EUC-04
Conifer stands	Without shrub undestory	PPIN-03	Shrubs	Shrubs < 0.5 m height	MAT-01
Conifer stands	With shrub undestory	PPIN-04	Shrubs	Shrubs 0.5 - 1.5 m height	MAT-02
Conifer stands	Mature	PPIN-05	Shrubs	Shrubs > 1.5 m height	MAT-03

Table 15. Fuel models from the Portuguese National Forest Inventory (Fernandes et al., 2006)

Cover	*Structural type*	*Cover*	*Structural type*
Acacia spp	CL	Other deciduous oaks	CL
Eucaliptus globulus	OT	*Pinus pinaster*	OT
	OL		OL
	CT		CT
	CL		CL
Quercus pyrenaica	CL	*Quercus suber*	OT
Diverse	OT		OL
	OL		CT
	CT		
	CL		CL

CL = closed and low stands: CT = closed and tall stands;

OL = open and low stands; OT =open and tall stands

Table 16. Mediterranean fuel models for Greece (Dimitrakopoulos, 2002)

Fuel Model	*General description*
Evergreen-sclerophyllous shrublands	Maquis up to 1.5 m
Evergreen-sclerophyllous shrublands	Maquis 1.5 - 3.0 m
Kermes oak shrublands	*Quercus coccifera*
Phrygana I	*Phlomis fruticosa*
Phrygana II	*Sarcopoterium spinosum*
Mediterranean grasslands	
Forest litter layer of Mediterranean pine species	

4. INVENTORY AND SAMPLING TECHNIQUES

An inventory component is a field data organic collection, following a defined study design, with statistical indicators from which it is possible to produce, even if in the uncertainty, an estimate of the quantitative variables (Pignatti, 1998). This is, also, an essential characteristic that differentiates the inventory process from a more common data collection method, which does not follow a specific protocol and assembles data obtained with different methodologies and through different time intervals. The choice of a specific sampling design, as well as a common terminology, and the availability of reliable and relevant gathered data contribute to:

- Develop and unify the knowledge regarding the study sphere;
- Express the demand of information (Bianchi, 1997);
- Program and monitor the inventoried resources management.

In general terms, a good classification system, must possess the following characteristics:

- Stability, namely the capacity to preserve its essential structure in cases of new information;
- Consistency, that is the possibility of adaptation to changes without radical changes in the structure;
- Compatibility, meaning the capacity of international concepts and classifications integration;
- Ecological significance, precisely the ability to inform ecological units, each one associated with ecological phenomena or parameters (i.e. energetic fluxes, evolution parameters, response to several disturb typologies, etc.).

As previously mentioned, one of the fundamental decisions regarding the development of an inventory is the choice of the characteristics to be inventoried in a sampling scheme. Thus, the following paragraph will treat the most common sampling schemes, and then address the studied parameters sampling techniques.

4.1. Sampling Scheme

The formalization of the procedure with which a sample is extracted from the population is the *sampling scheme.* The sampling scheme is also a mathematical procedure that allows the evaluation of parameters relative to a given number of observations on a defined area; such parameters are: the geometrical configuration of the samples (systematic, stratified, square, hexagonal, triangular grid); the spatial density (numbers of samples for unit area); the temporal frequency (numbers of samples for unit time). The collection of a sample from a population can be designed with several modalities, and the sampling scheme choice depends on the specific objectives of the planning and management of a survey, on the adopted physical models, the experimental conditions and on the estimated multiple uses of the collected data.

In general terms, the planning of a sampling scheme consists of selecting the amount and locations for adeguate sampling of a natural process spatially variable, with the aim to achieve a determined objective. In many cases the main goal is to choose, between several practically realizable configurations, for which the estimation error is the smallest. In other situations, however, additional factors, such as the cost of sampling and impediments of any type must be taken in consideration.

Complete enumeration

On small tracts, it is sometimes feasible to measure all plant of interest. The method has the advantage of determining the population mean rather than estimating it. A disadvantage is the high costs associated with complete enumeration tend to limit the application to small areas.

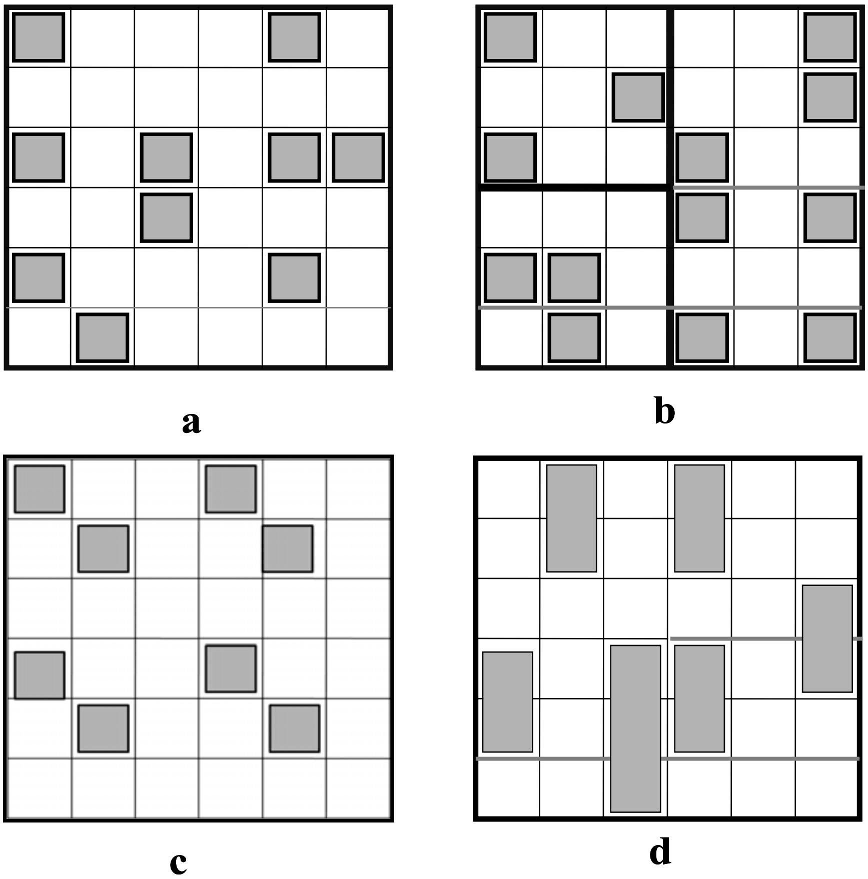


Figure 8. The most common sampling schemes: a) Simple random, b) Stratified random, c) Systematic, d) Cluster

Simple random sampling

Simple random sampling is the most basic of the sampling techniques, in which *n* distinct units are selected from the N units in the population in such a way that every possible combination of *n* units is equally likely to be the sample selected. The major advantage is the possibility to vary at any moment the sample size and to determine the sample proportions, obtaining the precision of the desidered estimate. Among the disadvantages, the production, sometimes, of distributions that do not represent the entire population; and the possibility of confusion of the systemic error with the random one.

With simple random sampling, the sample mean y_m is an unbiased estimator of the population mean μ. The estimate of the sample mean y_m and of the variance $V(y_m)$ of the mean

$$y_m = \frac{1}{n}(y_1 + y_2 + \ldots + y_N) = \frac{1}{n}\sum_{i=1}^{n} y_i \qquad (6)$$

$$V(y_m) = \frac{\sum_{i=1}^{n}(y_i - y_m)^2}{N(N-1)} = \frac{s^2}{N} \qquad (7)$$

where y_i is the observed value for the sample unit *i*-th, N is the total number of units, and s^2 is the sample variance. After the variance of the mean is estimated, it is possible to define the limits around the mean, based on this relation

$$L = y_m \pm t_\alpha (s^2 / N)^{1/2} \qquad (8)$$

where L is the limit; t_α is Student t with (n-1) freedom degree, and α is the chosen level of probability.

Stratified random sampling

In this approach the population is divided into non-overlapping subpopulations so that measurements within the subpopulation are more alike than in the original population. The technique often results in more precise estimates of parameters for a fixed cost that simple random sampling. The subpopulations are called *strata*, and a sample for each stratum at least should be selected. Because the selections in different strata are made independently, the variances of estimators for the individual strata can be added together to obtain variances of estimators for the whole population. A geographical region may be stratified into similar areas by means of some known variable such as habitat type, elevation, or soil type. Even if a large geographic study area appears to be homogeneous, stratification into blocks can help ensure that the sample is spread out over the whole study area.
The sample mean estimation on all strata (y_{mm}) and the variance of this mean $V(y_{mm})$ are:

$$y_{mm} = \frac{\sum_{h=1}^{J} N_h y_{mh}}{N} \qquad (9)$$

$$V(y_{mm}) = (1/N^2)\sum_{h=1}^{J} N_h^2 (s_h^2 / N_h) \quad (10)$$

$$s_h^2 / N_h = V(y_{mh}) \quad (11)$$

where N_h is the total number of units in the *h-th* stratum, J is the total number of strata, N is the total number on all the strata and s_h^2 / N_h is the variance of the *h-th* stratum mean. The estimation of the population mean or total will be most precise if the population is partitioned into strata in such a way that *within each stratum, the units are as similar as possible* (Thompson, 1992). The sampling scheme across transects, oriented along a determined direction or random, represents an example of stratified random sampling.

Systematic sampling

Systematic samplings means that the sample units are selected at equally spaced intervals over a population, partitioned into primary units, each one composed of secondary units. Systematic sampling is unbiased if the first unit is randomly selected. Unfortunately, there is no completely satisfactory way to compute confidence intervals from systematic samples. In general the pattern of measurements over a population will determine whether systematic or simple random sampling gives the most precise estimate. Three basic patterns can occur over time or space:

- **Irregularity.** Plot volumes that are distributed roughly in a random pattern over a tract. In this situation, systematic and simple random sampling are about equally precise.
- **Trend.** Because of site variations, plot volumes in certain areas of the tract are much higher than in other areas. The better spread of sample plots by systematic sampling often results in greater precision than simple random sampling.
- **Cycle.** Plot volumes are high in the lower elevation and lower in the higher elevations. If the spacing of inventory lines matches the cycle, systematic sampling is often less precise than simple random sampling. If the spacing does not match the cycles then the two techniques generally are about equally precise.

Cluster sampling

Although systematic sampling and cluster sampling seem to be opposites, the two designs share the same structure. Therefore, also in cluster sampling the population is partitioned into primary units, each one composed of secondary units. In particular, in cluster sampling, a primary unit consists of a cluster of secondary units, usually in close proximity to each other. Cluster primary units include such spatial arrangements as square collections of adjacent plots or long, narrow strips of adjacent units. The key point in both the systematic or clustered arrangements is that, whenever any secondary unit of a primary unit is included in the sample, all the secondary units of that primary unit are included. Even though the actual measurements may be made on secondary units, it is the primary units that are selected. The cluster sampling scheme is effective if the statistic unit list is not available or if its elaboration is impracticable, or if the variance among the groups mean is small compared to the total variability among the population units.

Multistage sampling

A cluster often contains too many elements to obtain a measurement on each. Or the elements may be so similar that a sample of elements provides a precise estimate of the cluster total. In either situation one might choose to obtain measurements on a sample of elements in a cluster rather than measuring all the elements: if, after selecting a sample of primary units, a sample of secondary units is selected from each of the selected primary units, the design is referred to as *two stage sampling*.

This scheme is favorable when both the simple sampling and the stratified would be too expensive because of the high cost to achieve all the units of samples, or when the variance between the secondary units is relatively low compared to that within the primary units.

4.2. Sampling Technique

Whatever the sampling scheme, the more important measurable quantity in community sampling are: 1) number of individuals or density; 2) frequency, the number of times a species is recorded; 3) cover, either of crown and shoot are or of basal area.

Many other structural life form criteria are measurable, for example, leaf size, bark thickness, or current year's twig diameters. Also, functional parameters, such as leaf persistence, vegetative reproduction, and shade-tolerance can be subjected to quantitative analyses, as has been demonstrated, for example, by Knight and Loucks (1969). In addition, there are several other measurable quantities, such as height, stem diameter, and biomass. The latter is measured in volume or obtained through cropping, and is usually expressed in fresh weight, dry weight, or gram calories per unit area.

Immediately below are reported the principal sampling technique used to measure the first three parameters listed above, that are always applied in vegetation sampling design. As mentioned in the chapter regarding the fuel characteristics, the biomass amount is fundamental because it represents the component of phytomass that is available during the combustion process. Therefore, the measurement techniques of this fundamental quantity will be added to the three parameter analysis.

4.2.1. Density

Density measurements in quadrats

This parameter relates to the counting of individuals per unit area. Counting is usually done in small quadrats in order to sample into the plant community (Figure 9). Afterwards, the sum of the individuals per species is calculated for the total area sampled in the small quadrats, and the result is expressed in terms of species density per unit area. This is perhaps the easiest analytical concept to grasp, but it often causes difficulties, like the *identification of individuals* (e.g. it is difficult to identify spreading shrubs where one individual begins and another ends), the *marginal effect of the quadrat* (e.g. when the boundary goes through an individual), and the *time* it takes to count herbaceous and shrubby individuals (Mueller and Ellenberg, 2003).

Figure 9. In the quadrats technique, counting individual plants by plant species or plant species by size classes usually is done in small quadrates (from Lutes et al., 2006)

Line transect

A line transect is characterized by a *detectability function* giving the probability that a plant at a given location is detected (Thompson, 1992). Usually, a line transect is used to make the density estimate, and there are several method that can be used. For estimating the variance of population density, estimators relying on sampling procedure rather than model assumptions about the population are emphasized. Most of the line transect density or abundance estimators are based on average detectability, effective area observed, or density of detections along the line.

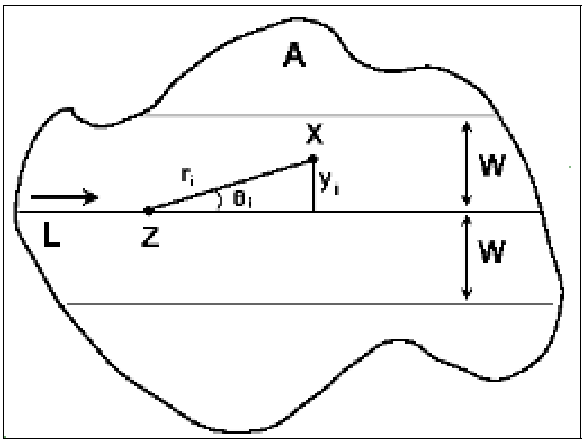


Figure 10. Schematic view of the method of line transect sampling

Three measurements can be taken for each individual sighted (Figure 10) (Gates, 1980; Anderson et al., 1979; Burnham et al., 1980):

– Sighting distance (r_i)
– Sighting angle (θ_i)
– Perpendicular distance (y_i)

The density of the population is estimated by

$$\hat{D} = \frac{n}{2La} \quad (12)$$

where $\hat{D}$ is the density of the sample per unit area, n is the number of samples collected on a transect, L is the total length of the transect, and a is a constant which must be estimated, but usually is the total area under the detection function

$$a = \int_0^w g(x)d_x \quad (13)$$

where $g(x)$ is the detection function, and W is the strip width.

4.2.2. Frequency

Frequency relates to the number of times a species occurs in a given number of repeatedly placed small sample plots or sample points, and it is expressed as a fraction of the total, usually in percent. In this case counting is not involved, just a record of species presence. Thus, it is a method more readily established than either the counting of individuals or the measurement of cover.

Quadrats. The most common technique to measure frequency is square quadrats, because it provides an objective assessment, similar to density and cover, but in contrast it is a non-absolute measure, because it is in part a function of the size and shape of the quadrat frames. The size and shape of the frequency quadrat influences the results of the frequency recorded.

Frequency is often considered a measure of abundance, thus related to density, but Greig-Smith (1964) has clarified that frequency rarely gives an indication of number of individuals per species (because the individual plants are not regularly or randomly distributed); rather it gives a certain indication of uniformity of distribution.

4.2.3. Cover

Usually cover is defined as the vertical projection of the crown or shoots area of a species to the ground surface expressed as a fraction or percent of a reference area. Instead of crown area, cover may also imply the projection of the basal area to the ground surface. Cover, as a measure of plant distribution, has been emphasized as being of greater ecological significance than density (Rice, 1967; Daubenmire, 1968), based on the observation that cover gives a better measure of plant biomass, in conjunction with a measure of depth and height, than does the number of individuals. Another advantage of cover as a quantitative measure is that nearly all plant life forms can be evaluated by the same parameter and thereby in comparable terms.

Quadrat-Charting method.

This technique is used in principal in low herbaceous vegetation, consisting in outlining the crown or the basal shoot and transfering the area occupied by matted plant onto a sheet of graph paper. This is primarily useful for permanent quadrats, because mapping a quadrat is time consuming. Similarly, photographic records can be used to outline the perimeter of an individual species, and subsequently, with the use of computer programs, the area can be calculated.

Point-Intercept method

A simpler method to evaluate cover is to reduce each of the small quadrats to a central point and to count the points that intercept a plant part. This method uses a narrow diameter sampling pole or sampling pins, placed at systematic intervals along line transects to sample within plot variation and quantify statistically valid changes in plant species cover and height over time (Figure 11). Plant species or ground cover classes that touch the pin are recorded as "hits" along a transect.

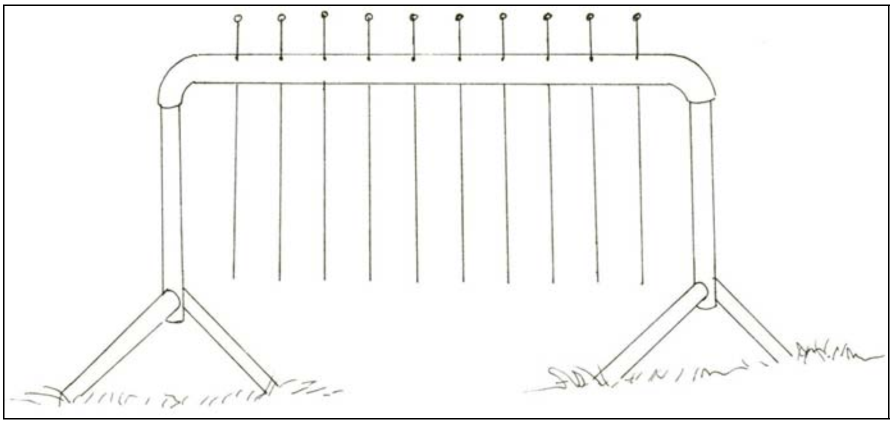


Figure 11. Example of a point frame with 10 pins (from Lutes et al., 2006)

Percent cover is calculated by dividing the number of hits for each plant species or ground cover class by the total number of points along a transect. This method is primarily suited for vegetation types less than 1 m in height and is particularly useful for recording ground cover. The Point Intercept method is considered one of the most objective ways to sample cover (Bonham, 1989), however, errors can be caused by plants moving in the wind or sampling poles lowered incorrectly (Caratti, 2006).

Line Intercept

Tansley and Chipp (1926) introduced the line intercept method, consisting of measuring the length of intercept for each plant that occurs over or under the tape. If basal cover is of interest, then the tape is placed at ground level. Percent cover is sampled by recording the length of intercept for each plant species measured along a tape by noting the point on the tape where the plant canopy or basal portion begins and the plant canopy or basal portion ends. When these intercept lengths are summed and divided by the total tape length, the result is a percent cover for the plant species along the transect. The line transect can be any length and, if modified, is usually done so based on the type of vegetation being sampled (Bonham 1989). In general, cover in herbaceous communities can be estimated with short lines (typically less than 50 m), while longer lines (50 m or greater) should be used in some shrub and tree communities. The line intercept method can only be applied to plants with rather solid, almost 100 percent crown cover (shrubs or matted plants) or relatively large basal areas (bunch grasses), and is best suited where the boundaries of individual plants are easily determined (Figure 12). Where crowns overlap in layered vegetation, the cover should be measured for each height layer separately. The layers or strata can be defined arbitrarily. In the case of trees, the upper size limit depends on visibility and the ease of making a vertical projection from the crown outline down to the underlying tape. The accuracy of the method depends largely on the accuracy of the vertical projection. The line intercept method has also been applied to counting individual plants, in conjunction with their measurement of cover (Buell and Cantlon, 1950).

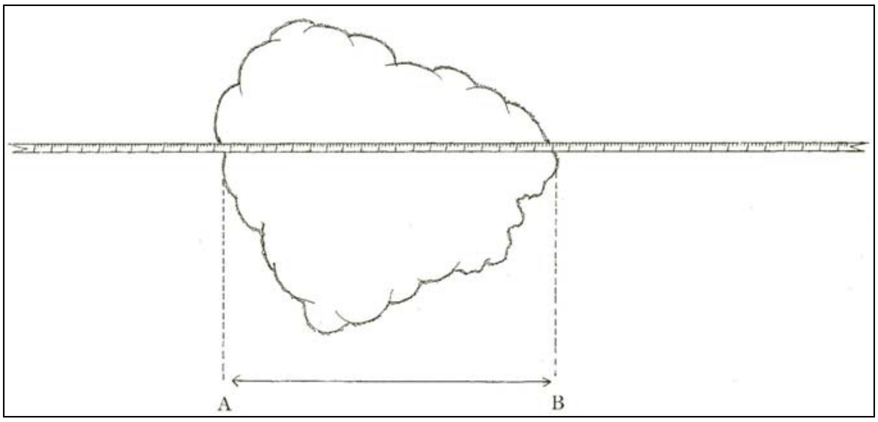


Figure 12. Example of measuring cover intercept along the measuring tape (from Lutes et al., 2006).

4.2.4. Fuel load

In forest fire research one needs to know the quantity of fuel present on the ground (van Wagner, 1968), and while fine fuel is easily measured by the collection and weighing of fuel samples, new approaches are needed for the estimation of larger-sized fuel.

Planar Intercept

The original sampling theory of this method, originally developed by Warren and Olsen (1964) for sampling slash, then further broadened and conceptualized by van Wagner (1968), was revised by Brown (1974) to allow a more rapid fuel measurement, still capturing the intrinsic variability of forest fuels, and to provide precise estimates of fuel load in the size classes important to fire behaviour (e.g. 1, 10, 100, and 1,000 hr and greater). The method is by far the most common sampling technique for sampling downed woody fuels for inventory projects in temperate forest, involving the count of woody fuel particles or measuring their diameters as they intercept a vertical sampling plane that is of a fixed length and height (Figure 13) (Brown 1970, 1974).

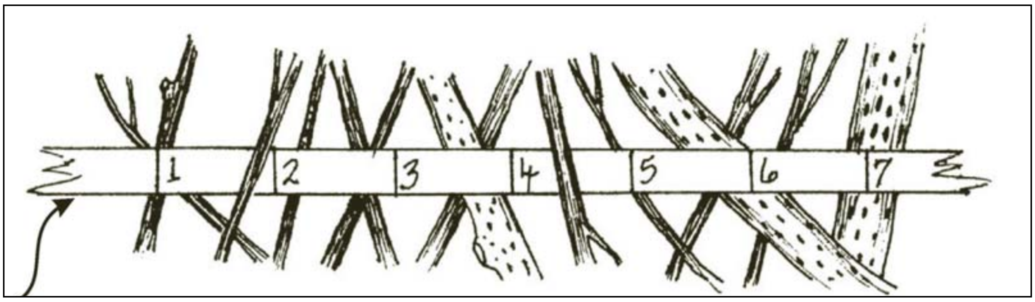


Figure 13. Exemple of talling pieces that intercept the sampling plane both above andbelow the measuring tape (from Lutes et al., 2006)

The sampling area is an imaginary plane extending from the ground, vertically from horizontal (not perpendicular to the slope) to a height 2 m above the ground. Pieces that intercept the sampling plane are measured and recorded. Frequently the term "line transect sampling" is used when discussing the planar intercept method.

The advantage of this method is that it is easy to use and can sometimes be scaled to match the sampling unit and fuel conditions by altering the dimensions of the sampling plane. However, this method only pertains to downed dead woody particles and may require a large number of sampling transects (bottom of sampling plane) under heavy and highly variable fuel conditions (Lutes et al. 2006). And, the scale for realistically describing fine fuel loadings (m^2) of all components is not possible with planar intercept because logs tend to vary at much coarser scales.

Fixed plot technique

These methodologies involved using a plot frame of a fixed area to delineate a sampling area, in which all fuels are collected, dried, and weighed to determine loadings (mass per unit area) (Harmon et al., 1986; Harmon and Sexton, 1996). These techniques include large circular or square plots along with a strip plot layout. The advantage of this method is that fuel components can be collected using the same plot frame or nested plot frames of varying sizes to accurately estimate variability at the appropriate scale. This is often the most accurate method of sampling fuels. The disadvantage is that the collection and weighing of material on the fixed plot is time and cost intensive, and therefore the method is used mostly for research efforts and rarely for operational fuel inventories. It is also difficult to determine the number of fixed plots to adequately capture the variability of different fuel components within the sample unit (stand, polygon, landscape) because the fuels are highly variable in space and time and are often clumped.

4.3. Photo series and photographic guides

Ground inventory procedures that directly measure site conditions (e.g., fuel loading and arrangement, vegetation structure and composition, etc.) exist for most ecosystem types and are useful when a high degree of accuracy is required. Ground inventory is time consuming and expensive, however. Thus, other methodologies have been developed to make quick, easy, and inexpensive determinations of fuel quantities and stand conditions when less precise estimates are acceptable. For years, fire managers in the United States have used photographs of fuel complexes as decision making and training aids. The photographs were often accompanied by qualitative ratings of fuel hazard; for example, the low, medium, high, and extreme ratings given to rate of spread and resistance to control (Hornby, 1936, USDA Forest Service, 1968).

Ryan and Johnson (2006) highlighted that only the development of the planar intercept fuel sampling theory (Warren and Olsen, 1964; van Wagner, 1968; Brown, 1971) and field inventory procedures (Brown, 1974), made it possible to measure (correctly and in relatively inexpensive way) the fuel loadings, and consequently to develop the National Fuel Classification and Inventory System (USDA Forest Service, 1974), which outlines a method to classify fuels using photographs and these fuel inventories. The result was the commonly used fuel sampling technique called the *photo series method*, a procedure that gives managers both quantitative and visual records of various fuel complexes. This method allows users to estimate the conditions of a field site by visually comparing the site to a series of photos. The first step using the photo series is to observe the characteristics of each fuel type, then select a photo series site that best matches the observed conditions (Fischer, 1981; Ottmar et al., 2004). Secondly, using the data summary tables, look up the value for the characteristic being estimated.

One of first purpose of this system, developed by Maxwell and Ward (1976a; 1976b), was a photographic serie for various levels of treated and untreated activity-created residues in the Pacific Northwest region of the United States. The plots in the study area were systematically inventoried using the planar intercept sampling technique (Brown, 1974). Fuels were inventoried in the 1, 10, 100, and 1,000 hr time-lag fuel size classes. Fuel and duff measurements were also taken. Permanent photo points were established so the photographs could depict a panoramic view of representative residue loadings (Figure 14). Color stereo paired photographs were taken from these points (Maxwell and Ward, 1976b).

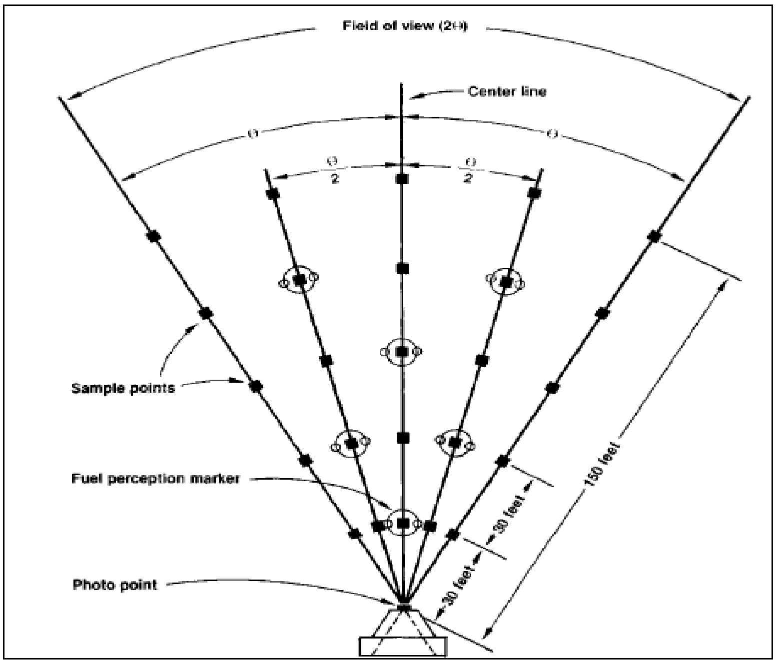


Figure 14. Scheme of the photo series methodology (from Maxwell and Ward, 1976b)

Inventory data were processed and average fuel loading and depths were calculated. The variance and standard errors in fuel measurements were recorded as an index of fuelbed variability and a measure of inventory precision. This inventory information was then used to develop residue treatment prescriptions.

With almost the same methodology, but a different purpose, Fisher (1981) designed a guide to help forest managers describe fuels, to estimate the amount of material, and to evaluate the fuel type specific fire hazard. The aim of the photo serie was "[…] to provide a relatively quick and inexpensive aid for accomplishing fuel appraisal over large forested areas" (Fisher, 1981).

Figure 15. Examples of photo series in the same forest cover type but different fire rating potential (from Fisher, 1981)

Other than the normal description of the stand and the site (i.e. age of overstory dominants, average slope, aspect, elevation, and fire ecology group) the photo series developed by Fischer are accompanied by a data sheet explaining the characteristics, summarized in Table 17. Several important fuel characteristics are reported in each photo: (1) the amount of fuel in different diameter classes, (2) the general condition of the fuel (sound versus rotten), (3) the distribution of the fuel over the area, and (4) the depth of the fuel (Fischer, 1981). Moreover, the data sheet for each photo also contained the rating for five different expressions of fire behaviour: rate of spread, intensity, torching, crowning, and resistance to control

Table 17. Summary of the characteristics gathered in the Fisher's (1981) photo series

Characteristics	*Source*
Forest cover type	Society of American Foresters (1954)
Habitat type	Pfister and others (1977).
Fuel data sample and inventory	Brown (1974)
NFDRS fuel models	Deeming et al., (1977)
Stylized fuel model	Albini(1976)

Recently, the Fire and Environmental Research Application (FERA) team, USDA Forest Service, developed, in the FCC sphere (see paragraph 2.2.2 and 5), a new fuels photo series, designed to quickly estimate fuel loadings and stand characteristics. The FERA photo series was developed selecting sites for the series with the aim of showing a range of conditions of several site attributes depending on the ecosystem type. Each photo site was intensively sampled to measure the fuel loadings and vegetation characteristics, using the procedures of Maxwell and Ward (1976b) as a guide. The innovation in this process is mostly due to the digitization of the photo series, which is a web-based application that provides access to the Natural Fuels Photo Series database and photographs. A user-friendly interface (Figure 16) allows users to browse, query, and download photo series data and high-quality photographs (Ottmar et al., 1998), and to connect to the FCC System, to choose the desired fuel model.

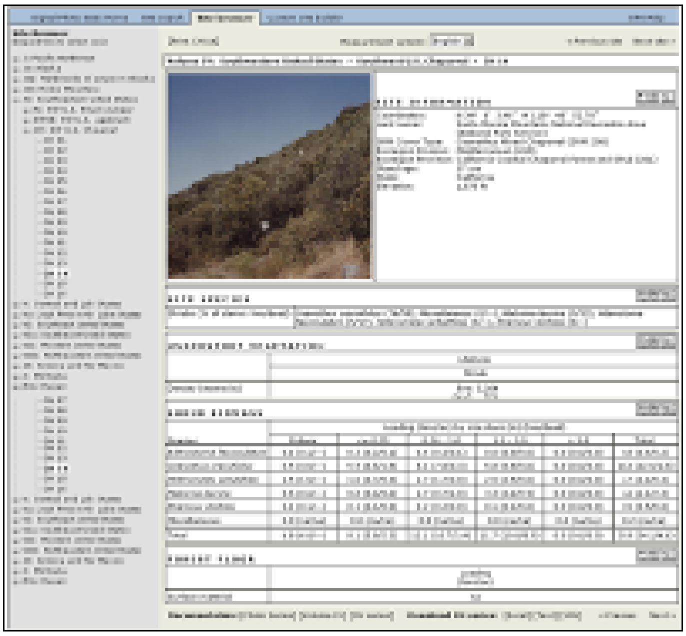


Figure 16. Example of the Digital Photo Series web pages

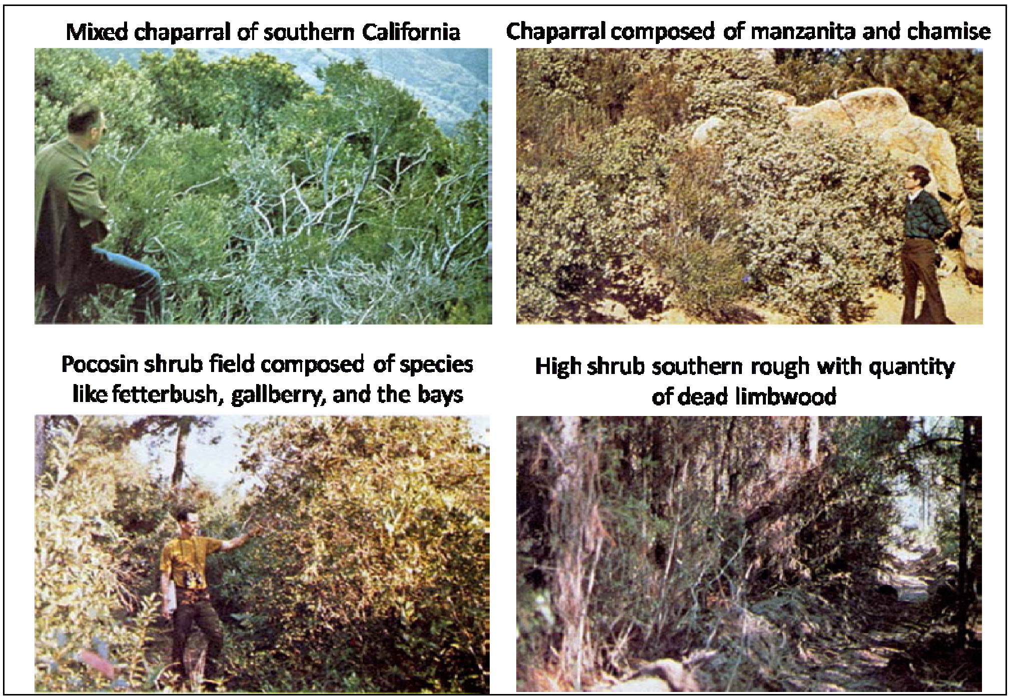
The photo series have several advantages; first of all, they are a good visual record of forest characteristics and attributes, useful for fire managers to predict fuel consumption, smoke production, fire behaviour, and fire effects during wildfires and prescribed fires, as well as supporting inventory. In addition, the photo series can be used to appraise carbon sequestration, an important factor in predictions of future climate, and to link remotely sensed signatures to live and dead fuels on the ground (Ryan and Johnson, 2006). Further, the photo series supply a good alternative to fuel inventories because, although providing all the same data, they are inexpensive.

The principal criticism, however, is that this technique is less accurate than the fuels inventories: for example, in the photograph series several fuel components, such as 1, 10, 100 hour downed woody) often are not visible, and they may not adequately capture the fuelbed conditions needed to estimate loadings of all fuel components at the appropriate scale (Lutes 1999, 2002). In addition, this technique is often not repeatable across time and space. Therefore, the photos series may be ineffective for predicting fire behaviour based on fuels inventories.

The photographic guides are slightly different compared to the photo series. In effect, even if they also concerned the easy fuel type quantification, they are more oriented to facilitate the fuel model assignment, depending on the vegetation type. In this system, small plots are selected as representative of defined fuel types; all fuelbed characteristics, necessary to define the fuel model, are described and measured, and afterward, some adequate photographs on the studied vegetation are taken. At present, several photographic guides summarized by fuel models are available in the literature (Anderson, 1982; Cruz, 2005; Scott and Burgan, 2005). The main problem with the photographic guides, as well the photo series, is related to high developing costs (Chandler et al., 1983), since the work of many persons at the same time is necessary.

The most famous photographic guides have been developed by Anderson (1982) who, implementing the Albini (1976) fuel models, supplied a descriptive key facilitating the model assignment by vegetation type, and by Scott and Burgan (2005), who broadened the 13 Anderson's fuel model to 40 (see paragraph 2.2). The 13 original models (Albini, 1976; Anderson, 1982), used exclusively to predict the behaviour of the surface fire and the flame front, were classified into four groups—grasses, brush, timber, and slash. The differences in fire behaviour among these groups were basically related to the fuel load and its distribution among the fuel particle size classes, assuming that the fuel bed is homogenous and continuous. Therefore, after visual estimate, the user may decide which fuel groups are represented, observing the location and positioning of fuels in the field (Figure 17). Recognizing the features that distinguish one fuel group from another, the subsequent selection of a fuel model can be simplified. In addition, the guide contain information concerning the following variables: dead fuel load for size class, live fine fuel load, SAV ratio for woody fuel and live herbaceous fuel and dead fine fuel, thickness of the fuel bed, humidity of extinction of the dead fuel and calorific content of the live and dead fuel (Anderson, 1982).

The Scott and Burgan (2005) fuel complex information, instead, were compiled from several volumes of the Natural Fuels photo series (Ottmar and Vihnanek 1998, 1999, 2000, 2002), and subsequently the range of fuel complex characteristics collected suggested the spectrum of fuel conditions for which fuel models were needed. In these photo guides, fuel type is subjectively grouped by fire-carrying fuel type and, using a set of three photos, every fuel type is accompanied by a brief description, unlike the Anderson's photo guide (1982) which had only a summary of the fuel parameters. In addition a pair of charts depict fire behaviour over a range of mid-flame wind speeds.



Total fuel load (dead and live), < 6 cm (t/ha)	Dead fuel load, 10 cm (t/ha)	Live fuel load, foliage (t/ha)	Fuel bed depth (m)
32.50	12.50	12.50	1.82

Rate of spread (m/hr)	Flame length (m)
3.73	5.79

Figure 17. Example of Anderson's (1982) photo guide: fuel model n° 4, Chaparral

In Europe, the countries that have developed photographic fuel guides are Spain and Portugal. In the 1990, ICONA (Instituto Nacional para la Conservacion de la Naturaleza - Forestry, Fishery and Wildlife Service) started the development of the fuel model photographic key considering wide areas representing an high degree of homogeneity from a forestry point of view. The methodology follows the Anderson's photo guide (1982); therefore also the ICONA photo guide is an aid to determining fuel models for estimating fire behaviour. The attention was focused on the fuel types (grouped as grasses, shrubs, timber, and residuals from managements) that carry fire; after estimating the height and arrangement, a visually comparison between photos and the real fuel allows the user to classify the latter, through a dichotomous key, among one of the 13 system's models. Finally, every model was characterized exclusively by height and fuel load. Different from Anderson (1982) and Scott and Burgan (2005), the ICONA models have not a pre-determined dead fuel extinction moisture, but it is possible to compute it through a series of tables, taking into account the relative weather condition and the exposition of the fuel.

Unlike Spain, Portugal built guides for specific regions instead the whole country (Almeida et al, 1995; Cruz, 2005). The photographic guides were based on the identification of the most recurrent fuel complexes in the Sierra da Arrabida and Central Region, respectively, with the aim to supply fuel complex quantification in a less onerous and quicker way compared to ground inventory (Cruz, 2005), and to develop fuel models applicable to several areas of fire management. This process went through the identification of the classifiable situations on the basis of the structural characterization of the different fuel layers, the vertical arrangement and the fuel load available to combustion.

Both guides, in different ways, supplied the quantitative description of fuel load in the dimensional classes and the potential fire behaviour, modeled with the BEHAVE fire simulator program, but they were different in the description of the fuel complexes. Almeida and collaborators (1995) focused on the vegetation type through the dominant species, whereas Cruz (2005) paid more attention on the fuel types carrying the fire (grouped into grasses, shrubs, residuals from managements, stand susceptible and not to crown fire propagation), every one subdivided into fuel complex according to its arrangement and potential fire behaviour (Figure 18).

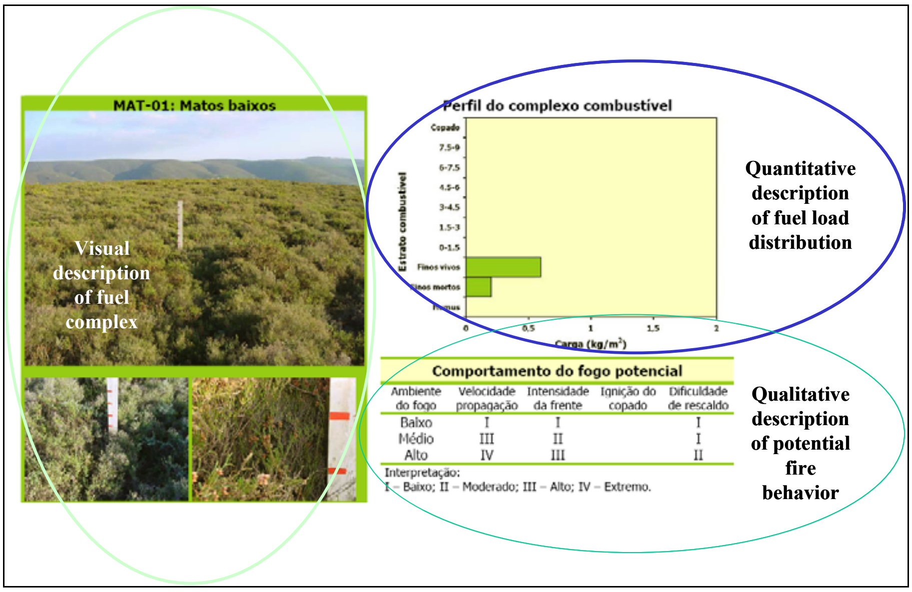


Figure 18. Example of Cruz (2005) photo guide: matorral

5. FUEL MAPPING

Regarding the basic concepts of mapping vegetation, Kuchler (1967) affirmed that "vegetation maps were not invented by one man at one time like the steam engine or the electric light bulb", but the story of vegetation map evolved with very slow acceleration, a regionally spot development, and only in the first quarter of the twentieth century it did a real improvement among nations. Similarly, the evolution of fuel maps, regarding the fuel characteristics and typology, which are tightly correlated to the vegetation, was slowly and in principal developed regionally (actually in the United States). Subsequently, the fuel map's use accelerated its evolution and spread around all countries only in the last quarter of the twentieth century.

This was due to several reasons that have been pointed out only in the above mentioned time lag. Although fire plays a major role in the structure and the functioning of many forested ecosystems, the exclusion and the *quasi* constant suppression of wildland fire from forests was successful by many countries. This legacy of fire exclusion perturbed natural fire regime and resulted in excessive accumulation of forest fuel. Fuel that would have previously been consumed by fire remains unburned (Rollins et al., 2004). But the subsequent recognition of both the importance of fire in ecosystem structure and functioning, and the increasing fire hazard from fire in some areas (Arno, 1976; Habeck, 1985), required the development of spatially explicit, comprehensive information on fuel for long term planning, focused on restoring and managing fuels, fire regime condition (Rollins et al., 2004) and assessing of risk of fire. Thus, fuels maps are a fundamental part of fire management activities such as prescribed fire planning, suppression strategies, smoke management, and fire effects (Ohlen et al., 2000; Keane et al., 2001).

The importance of fuel maps to fire management depend on the temporal and spatial scales involved as well as management objectives (Burgan et al., 1998;

Keane et al., 2001). Table 18 shows several spatial scales and possible fuel map applications at the corresponding scale.

Usually, global, national, and regional fire danger assessments are evaluated using *coarse scale* fuel maps (Werth et al., 1985; Chuvieco and Martin, 1994; Burgan et al., 1998), to more effective planning, allocation, and mobilization of suppression resources at weekly, monthly and yearly evaluation intervals. Moreover, they are also a source of useful input for simulating regional carbon dynamics, smoke scenarios, and biogeochemical cycles (Running et al., 1989; Kasischke et al., 1998; Leenhouts, 1998).

Fire danger programs were also aided by *intermediate-scale* digital fuel maps (Chuvieco et al., 1997), but generally the spatial extent of these mapping efforts was at state or region level. In any case, the mid scale fuel maps are used to analyzing the ecosystem health, to locate and rate fuel treatments, and evaluate fire hazard estimates and risk for land management planning (Pala and Taylor, 1989; Ottmar et al., 1994; Salas and Chuvieco, 1994; Wilson et al., 1994; Cohen et al., 1996).

Finally, fine resolution fuel map are used to obtain realistic simulations of spatial fire growth and behaviour: coarse spatial resolution, where a single fuel model is assigned to large polygons may not produce reliable fire spread predictions because the homogeneous conditions assumed by the single fuel model do not reflect actual fuel variability across the large area (Finney, 1998). Furthermore, landscape-level fuel maps may describe with a high level of detail the distribution of vegetation type that differ in their fuel loads, for planning and implementing prescribed burns (Bailey and Mickler, 2007)

Both fine scale and landscape level fuel maps are essential for local managers because they also describe fire potential for planning and prioritizing specific burn projects (Chuvieco and Congalton, 1989; Pala et al., 1990; Maselli et al., 1996; Maselli et al., 2000), to simulate planned and unplanned fires (Keane et al. 1998*b*) or to study historical fires (Arca et al., 2007).

Table 18. Description of fuel map development across three scales (from Keane et al., 2001)

Fuel Maps	*Spatial Scale*		
	Coarse	Mid	Fine
Primary application	Fire danger	Fire risk and hazard	Fire growth
Fire uses	Plan and allocate resource	Locate and prioritize treatment areas	Simulate fire behaviour, predict fire effects
Other uses	Global carbon budgets	Forest health assessment	Simulate ecosystem and fire regime dynamics
Mapping approach	Indirect, gradient model	Direct, indirect, gradient model	Field reconnaissance, direct, gradient model
Mapping entities	Land use type	Fuel models	Fuel model, fuel loadings
Possible pixel sizes	500 m - 5 km	30 - 500 m	5 - 30 m
Imagery	AVHRR, MODIS	MODIS, MSS, TM	TM, SPOT, AVIRIS, IKONOS, aerial photos

5.1. The approaches for mapping fuels

Four approaches to fuel mapping have been found useful: 1) field reconnaissance; 2) direct mapping; 3) indirect mapping and 4) gradient modeling (Keane et al., 2001).

Without doubt, field surveys are the first methodologies developed in the early 20th century, focused on the discrimination of fuel type, defined as a complex function of vegetation characteristics, with great level of detail. Consequently, field surveys are still indispensable for fuel type mapping, either as the basic source of data or for assessment of products generated at a lower level of detail, or to parameterize each fuel type (Chuvieco et al., 2003).

The first basic concept on "modern" fuel type mapping was defined by Lee (1941), considering that the use of aerial photograph technique was useful in "*providing information accurately, cheaply and rapidly*", pointed out the equal usefulness to some phases of fire control planning. "*From the stand point of area, perhaps the most extensive class of information to assemble in a fire-control plan is the nature and location of the fuels. Collectively speaking, this is the fuel type map*" (Lee, 1941). This concept was later expanded by Lund (1969), involving not only vegetation mapping but also knowledge of the type, amount and distribution of surface fuels.

In the middle sixties, some authors predicted that satellite remote sensing would revolutionize fuel type mapping (Adams, 1965). Salas and Chuvieco (1995) summarized the advantage of satellite observation, pointing out that:

- Data are acquired systematically and consistently;
- Information is obtainable from non-visible regions of the spectrum (near, middle and thermal infrared, microwaves);
- Fuel type maps are easier to update, since satellite images are obtained regularly;
- Satellite remote sensing offers global coverage and enough spatial resolution.

Additionally, satellite sensors provide digital information that can easily be tied into other spatial databases using GIS analysis, which can be quickly imported into running fire behaviour and growth models (Tian et al., 2005).

5.1.1. Field reconnaissance

Field reconnaissance involves traversing a landscape on the ground and recording the extent of similar fuel conditions in notebooks or on paper maps (Keane et al., 2001). Except aerial photographs, other digital support, as satellite images, are not used.

One the first fuel type maps was generated in the United States by Hornby (1936), who mapped more than six million hectares in the northern Rocky Mountains, with the help of the Civilian Conservational Corps, which covered the national forest and described the fuel conditions. The fuel classification used by Hornby was ahead of its time; instead of describing actual fuels loadings, he mapped two factors that defined what he called fuel type: 1) the resistance to control and 2) the rate of fire spread, linking fire behaviour with fuel characteristics.

One of the primary advantages of the reconnaissance strategy is that fuels are mapped from actual conditions observed on the ground (Hornby, 1935). In the field reconnaissance approach, mapping errors are limited, resulting in essentially erroneous fuel type assessments or improper stand delineations on paper maps; moreover, the steps to create fuel maps are reduced, which also minimizes error. On the other hand, this approach requires a large amount of human effort, high cost, and often is highly subjective in the fuel type assignment. The difficulty of conducting a ground survey is evident in the work carried out by Show and Kotok (1929), who dedicated 10 years of fieldwork to obtain an 8 class vegetation map covering 6,000 hectares in Northern California (USA), and who admitted that their work was unfinished. Lastly, resultant maps were not especially useful for other fire management concerns.

5.1.2. Mapping using the remote sensing

The limitations of field work in terms of spatial coverage and cost made it clear that other methods were required for operational fuel type mapping. Remote sensing and digital image processing are tools that have revealed great importance to classifying and quantifying the distribution of fire fuel types and conditions. Vegetation community types, gradients and density categories can be classified from airborne or satellite image data by visual image interpretation or through statistical pattern recognition routines (Stow et al., 1993). Two different methodologies, according to Keane and others (2001), can be distinguished: the direct fuel mapping approach and the indirect fuel mapping approach.

5.1.2.1. Direct fuel mapping using remote sensing

This approach refers to the direct assignment of fuel characteristics to the results of image classification or photo interpretation (Verbyla 1995). Several authors state that this approach has the highest success when estimating total living and dead biomass in grasslands and shrubands (Friedl et al., 1994; Chladil and Nunez, 1995) but, in the case of forested ecosystems it has a limited use because of the canopy obstruction (Elvidge, 1988). The use of remote sensing in creating fuel maps is an extremely difficult and complex process, as it requires expertise in image classification, fire behaviour, fuel modeling, fire ecology, and GIS analysis. However, use satellite images is becoming the primary and preferred method for assessing fuels (Rollins et al., 2000).

Traditionally, aerial photos have been the most common remote sensing data source (Lee, 1941; Lund, 1969; Morris, 1970; Muraro, 1970; Oswald et al., 1999). For mapping fuel type distribution at the fine scale, although satellite data is increasingly used, aerial photography continues to be a tool of choice (Oswald et al., 1999). Lee (1941) was among the first to propose the use of photo-interpretation techniques to discriminate fuel types in aerial photography, although he pointed out some limitations as well, such as confusions caused by illumination differences. The introduction of natural color improved vegetation mapping (Lund, 1969), since they provide relevant spectral information for the discrimination of species composition or cover type (Scott et al. 2002). In the last decade, infrared-color photographs have also provided relevant spectral information for the discrimination of fuel type (Bertolette and Spotskey 1999), combined often with extensive fieldwork, to produce detailed inventory of fuel properties.

Regarding the use of satellite image, Kourtz (1977) was a pioneer in this effort, introducing the main techniques of digital fuel type classification using satellite remote sensing images (Landsat-MSS); he obtained nine fuel type classes within his study area near Ottawa (Canada), employing multitemporal images to take advantage of the temporal variability among fuel types. Following this research, fuel type mapping from imagery was attempted by several authors: most commonly the generation of fuel maps from remote sensing images was based on the analysis of medium- to high-resolution 30-0.61 m sensors, such as Landsat Multi Spectral Scanner (MSS) and Landsat Thematic Mapper (TM) data (Agee and Pickford, 1985; Castro and Chuvieco, 1998; Riano et al., 2002).

Landsat products represent a good compromise between spectral and temporal resolutions with an adequate spatial coverage for normal operational fire management applications (Riaño et al., 2002). For example, single scene Landsat TM images was used to classify fuels (Root and van Wagtendonk, 1999), and the maps produced from that analysis were used to predict the behaviour of two large wildland fires that were allowed to burn to meet resource objectives, plan for extensive prescribed fires set by managers, and to make tactical decisions on a wildland fire that was being actively suppressed. In each case, operations were enhanced by the availability of accurate information on fuels. New sensors, such as hyperspectral and radar were also tested at small scale, having great potential for mapping vegetation properties because of their high spectral resolution (Chuvieco et al., 2003). For instance, the Airborne Visible/Infrared Imaging Spectrometer imager with 224 bands (AVIRIS) was used for the spectral characterization of fuel types (Roberts et al., 1997).

Landsat TM was also used in large applications at middle and coarse scales, for example, to map fuels models in Yosemite National Park, USA (van

Wagtendonk, 1999; van Wagtendonk and Root, 2003), with the objective of testing the applicability of the Normalized Difference Vegetation Index (NDVI) to map fuel models. An unsupervised classification algorithm was used to define 30 unique spectral-temporal classes of NDVI values. Combinations of graphical, statistical, and visual techniques were used to characterize the 30 classes and identify those that responded similarly and could be combined into fuel models. Salas and Chuvieco (1994) classified TM imagery directly to 11 of Anderson's (1982) fuel models, then assigned vegetation categories to each fuel model to compute fire risk on a large landscape in Spain. Stow and others (1993) classified chaparral shrub fuel characteristics across mid-scale landscapes in California using three images generated from the transformation on TM multispectral data. Van Wagtendonk and Root (2000) used multi temporal Landsat TM imagery for developing techniques to identify fuel types based on seasonal changes in plant phenology. Such analysis techniques would allow the discrimination of fuels based on both spectral and temporal characteristics.

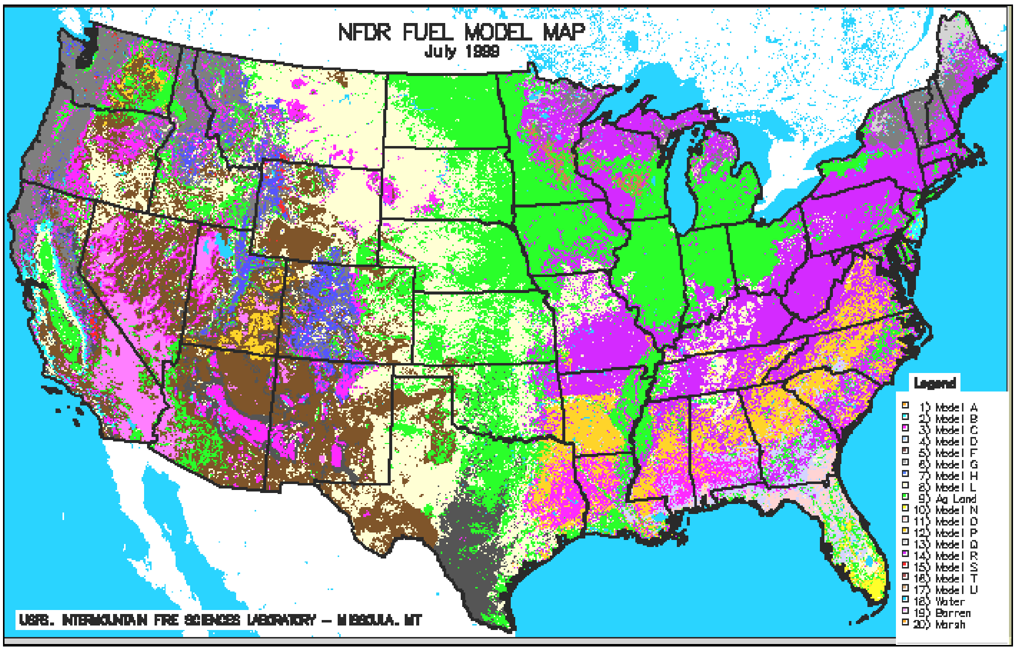


Figure 19. National Fire Danger Rating system (NFDR) fuel model map (http://www.fs.fed.us/land/wfas/fuels)

Other efforts concentrated in coarse spatial resolution sensors have used the Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectro-Radiometer (MODIS) images. McKinley and collaborators (1985) computed the Normalized Difference Vegetation Index (NDVI) and the principal components from an AVHRR satellite image, classifying them directly to fuel class, which were subsequently used as input to an Initial Attack Management System (McKinley et al., 1985). Another example of AVHRR use at global scales is the 1 km resolution fuel model map based on a 159 class land cover characteristics database, developed by the US Geological Survey's Earth Resources Observation System (EROS) in 1991. The initial vegetation map was produced clustering eight monthly composites of AVHRR NDVI data (Loveland et al., 1991). The main advantage of the AVHRR sensor is the possibility of incorporating multitemporal data because of its high temporal but low spatial resolution. The classification accuracy of fuel types may be low when the fuel beds and land-use patterns are very complex, such as those found in the Mediterranean basin (Riaño et al. 2002).

MODIS satellite data were used in a highly representative Mediterranean ecosystem in Italy, ,with the aim of delineating forest fuel type (Lanorte and Lasaponara, 2007a) in fragmented areas, using two classification approaches, Maximum Likelihood classification algorithm (ML) and Spectral Mixture Analysis (MTMF) (Figure 20). Results showed that MODIS data provided a valuable characterization and mapping of fuel types with an high classification accuracy (> 73% for ML classifier and > 83% for MTMF).

The advantage of the direct approach is its simplicity. Classifying fuels directly from imagery reduces errors due to biomass calculations, and translation errors from vegetation classifications, and image processing steps are minimized (Keane et al., 2001). On the other hand, there are several disadvantages, especially in forested areas. Passive remotely sensed data, such as LANDSAT and MODIS, cannot penetrate into the forest canopy (Lachowski et al., 1995; Elvidge, 1988), and this not allow the sensing of surface fuels, especially differentiating the height and understory vegetation (Keane et al., 2000).

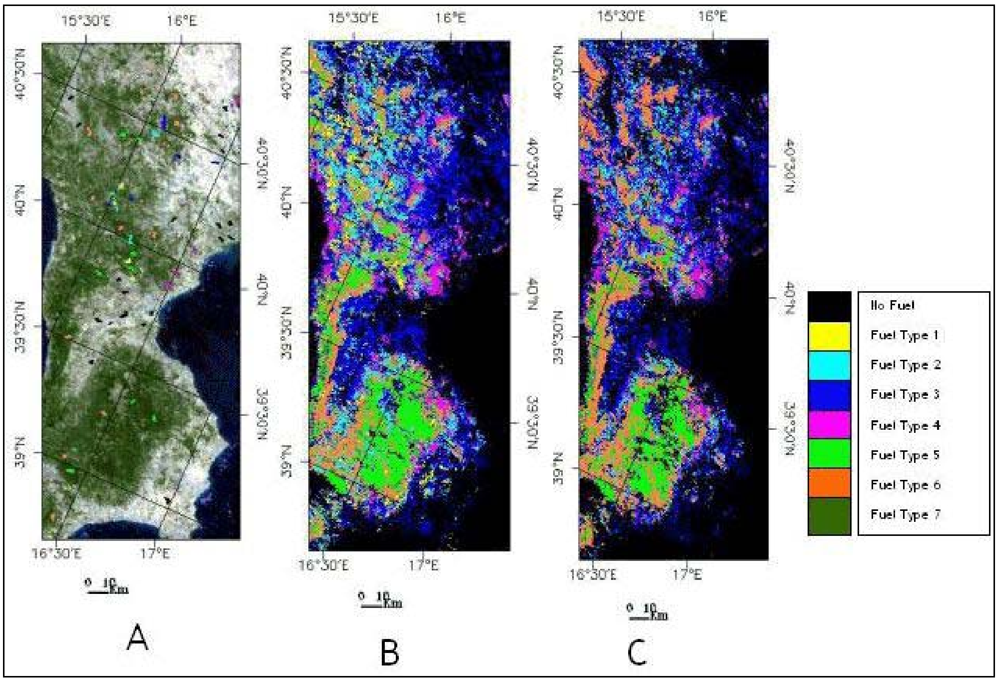


Figure 20. Fuel maps obtained from the processing of MODIS data: (A) Modis Region of Interest; (B) Modis ML classification; (C) Modis MTMF classification (Lanorte and Lasaponara, 2007a)

For that reason, sometimes two independent image classifications of surface and crown fuel models are required for most fire growth applications, and there is still a high probability that these two classifications will not be spatially congruent or consistent. The use of another sensor to estimate the canopy height would help to identify the fuel type, as SPOT-HRV, which has been used to estimate this parameter using empirical approaches by De Wulf and collaborators (1990).

5.1.2.2. Indirect mapping remote sensing

Indirect mapping remote sensing approach recognizes the limitations of imagery to directly map fuel characteristics, and uses other ecosystem characteristics as surrogates for fuels. This approach assumes that biophysical or biological properties can be accurately classified from remotely sensed imagery, and that these attributes, most often related to the vegetation, correlate well with fuel characteristics or fuel models (Keane et al., 2001).

Coarse scale imagery such as AVHRR was used to discriminate broad vegetation types or land cover classes, and these classes appear to correlate well with fuels because vegetation categories are so broad that they generally have unique fuel characteristics. For example, the Omernik's ecoregions (1987) were used several times, jointly with the AVHRR land cover classification (Loveland et al., 1991), or the North American Land Characteristics database (Loveland et al., 1993) to develop an NFDRS fuel model map for the United States (Burgan et al., 1998) and a NFDRS fuel map of California. Ottmar and collaborators (1994) assigned a wide variety of fuels characteristics to combinations of vegetation cover and structure types for the Interior Columbia Basin Ecosystem Management Project (Quigley et al., 1996). This indirect approach was also used for mid scale fuel mapping projects. In the United States fire fuel model maps of the North Cascades National Park were developed by Root et al. (1985) from plant community maps created from 1979 Landsat MSS imagery and environmental relationships. They assigned both the NFDRS (Deeming et al., 1977) and the Anderson (1982) fuel models to each classified vegetation type. A similar approach was used by Miller and Johnston (1985) assigning NFDR fuel models to vegetation maps created from classifications of MSS and AVHRR imagery. European examples were provided by Salas and Chuvieco (1995) who combined the use of Landsat TM data with digital terrain models (DTM), improving the accuracies for discriminating some fuel types, and by Riaño and others (2002) who used not only the DTM but also the analysis of texture bands, as a tool to study the spatial heterogeneity in vegetation and multitemporal trends. Roberts and others (1998) used a different approach when an AVIRIS imagery coupled with spectral mixture analysis was used to classify vegetation fraction, cover, and water content in California, which were related to fuel loadings directly sampled on the ground.

The indirect approach is used for many reasons. Above all, there are many vegetation classifications available to name spectral clusters or describe training area (Anderson et al., 1993) and the vegetation types can be consistently identified in the field with little errors (Eyre, 1980).

The major disadvantage of the indirect approach is that fuels are not always correlated with vegetation characteristics or land-use categories. Most satellite imagery and other remotely sensed products are better suited for differentiating between vegetation types than fuel types. Furthermore, vegetation classification categories may be too broad to represent unique fuel characteristics accurately. Another disadvantage is that vegetation layers are often composed of stands that may be too coarse for fine scale fire spread simulation. Homogenization of the fine scale may result in smothered fire spread predictions that may not be realistic (Finney, 1998).

In any case, vegetation maps created from this approach are often used for other land management applications, and the fuel maps can easily be updated as additional field data are collected or new vegetation maps are produced.

5.1.3. Ecological modeling

This approach, which uses environmental gradients and biophysical modeling, introduced in the first decades of the twentieth century by Gleason (1926) and Ramensky (1930), was improved and refined in the United States by Bray and Curtis (1975) and Whittaker (1967, 1975). Traditionally, it is often defined as a quantitative description of the distribution of a plant species along one or more environmental gradients, such as climate, topography, and disturbance, which directly influence vegetation and fuel dynamics. Once key gradients are identified, they can be mathematically represented in a gradient model to quantify those gradients across a landscape and predict changes in species composition (Kessell, 1979).

Gradients can be topographical (e.g. elevation, aspect, slope) biological (e.g. successional stages), geological (e.g. soils, landform), or biogeochemical (i.e. evapotraspiration, productivity, nutrient availability). Austin and Smith (1989) define three types of environmental gradients, contributing a useful taxonomy for discussion:

– Indirect gradients (i.e. slope, aspect, elevation),;
– Direct gradients (i.e. temperature, humidity);
– Resource gradients (i.e. energy and matter used or consumed by plants such as light, water, and nutrients).

The first has no direct physiological influence on plant dynamics, unlike the direct and the resource gradients, which are important for mapping vegetation and ecosystem characteristics because they fundamentally define the potential species niche (Austin et al., 1983; Austin, 1984). Moreover, Muller (1998) adds spatial and temporal dimensions to those three gradient types, thus introducing the functional gradient as the fourth type.

Franklin (1995) mentioned that the indirect factors were the most easily measured environmental gradients, influencing vegetation composition, instead of the direct ecological factors, which were often inferred from these secondary gradients. For example, changes in species composition by elevation are actually a result of changes in temperature and precipitation with altitude (Kessel, 1979; Muller, 1998), but it is simpler to map than the direct factors.

Several studies described or mapped plant communities through environmental variables. For example, soils, geology, topography and climate have been used by Pattern (1963) to map vegetation in Montana, USA. The same gradients, along with clear-sky radiation, have been used to predict the distribution of live oak in California (Davis and Goetz, 1990). Recently, some studies have proposed the possibility of mapping other characteristics other than vegetation using direct gradient methodology (Keane et al., 2002), such as potential natural vegetation (Walker et al., 1993) or fire regime (Romme and Knight, 1981; Barton, 1994; Rollins et al., 2004). On the other hand, further research identified new direct gradients in a group of ecophysiological variables that govern vegetation dynamics (Austin, 1987; Waring and Running, 1998), such as pattern of carbon fluxes, primary productivity (Williams and Rastetter, 1999), soil moisture, and nutrient fluxes (Nixon, 1995). Those important ecosystem processes, such as biogeochemical cycling, can be correlated with fuels to provide a temporal and spatial framework for creating dynamic fuel maps: low fuel loadings in a stand, for example, may be explained by low precipitation, high evapotraspiration and shallow soils. Gradient analyses provide an ecological context in which to understand, explore, and predict fuel dynamics.

There are several advantages of using direct gradient modeling over other mapping schemes. Quoting Keane and collaborator (2002), who reviewed these advantages, gradient approaches are preferable to expert system approaches where decision rules are based on opinions rather than empirical data. Gradients are often *scale-independent* (meaning the same gradients may be used to predict fuel characteristics across many spatial scales), and *flexible*, and *portable* (gradients are similar in lands outside the sampled areas and the landscape models may be extrapolated to unsampled areas) (Franklin and Woodcock, 1997; Gosz, 1992; Whittaker, 1975).

The major criticism of most gradient modeling approaches is that the results describe potential rather than existing conditions (Keane et al., 2002). Moreover synthesis of the results of gradient analysis into a prognostic gradient model is difficult because of interrelated factors. Many environmental gradients that influence the vegetation dynamics are still unknown or difficult to characterize across a landscape (Whittaker, 1967), or the set of gradients that influence ecosystems may be entirely different from one landscape to another. One other problem with this approach is that biophysical gradients do not provide a complete description of existing biotic conditions, and remotely sensed data are often needed to spatially portray vegetation-based gradients such as succession classes or cover types. Gradient information is best used to describe the potential of a landscape or stand to support a fuel model or set of models (Kessel, 1979; Keane et al., 1997). Another disadvantage is that this approach requires abundant field data, complex ecosystem models, and intensive statistical analysis requiring extensive expertise in ecological sampling, simulating modeling, and statistical examination. But, once a gradient framework is established with continuous calibration of key variables, it can be used by all land management agencies (Keane et al., 2002).

5.2. New approaches for mapping fuel

Of the four fuels mapping approaches, no one approach appeared to create the most accurate maps. This is often due to the lack of information about accuracy assessment, and inadequate field data sets in estimating accuracy (Keane et al., 2001). All approaches require extensive field sampling to construct accurate maps and broad expertise in fire and fuels modeling, image processing, and GIS techniques (Keane et al., 2001).

It is possible to assess whether that certain approaches are better for some situations than others: the direct approach is better for grassland and surface fuels but worse quantifying the entire array of fuel because the convoluted surface and crown spectra are difficult to decouple; whereas the indirect approach is better for forest fuels, but the fuels mapped may not be correlated with vegetation characteristics or land-use categories.

Recently, the most common difficulties in mapping fuels from remotely sensed imagery (with both the direct than the indirect approach) were reviewed by Keane and collaborator (2001):

– many fuel types. Live and dead woody and herbaceous in the different size categories comprised within the fuel bed, and they are not adequately discriminated, due to the disparity between particle size and image resolution;
– stand structure and composition are unable to be accurately discriminated by remotely sensed imagery products to the detail or resolution useful in resource management (Redmond and Prather, 1996);
– fine fuels, important for fire spread, are too small to be detected accurately by satellite images, because they are often hidden by canopies, undergrowth vegetation and logs;
– fine fuels, are typically too variable across time and space (Brown and See, 1981; Harmon et al., 1986; Agee and Huff, 1987) to be mapped using most commercial imagery resolutions (Finney, 1998).

The fuel variability, within a stand often equals the variability of fuels across the landscape (Jeske and Bevins, 1979; Brown and Bevins, 1986), due to several environmental causes, such as a single wind event, the rate of fuel accumulation and decomposition, the stand history (insect, disease, harvesting, climatic events and fire). As a result, fuel characteristics can be quite variable across the resolution of most remotely sensed imagery and any generalized representation of the fuelbed is difficult to apply to the entire landscape (Keane et al., 2001).

5.2.1. Integration of remote sensing and biophysical settings

Some mapping and image classification efforts illustrate the power of integration of environmental information with satellite imagery to develop better ecological maps, and how accuracy can be significantly improved with the assimilation of different information that can be acquired from satellite imagery, aerial photo interpretation, or field reconnaissance and biophysical settings. The first can be used to map cover types and structural stages across a region (Hessberg et al., 1998; Keane et al., 1998b; e.g. Bobbe et al., 2001), while the last can be used to stratify cover type and structural stage (Keane et al. 1998b; Menakis et al. 2001). For example, Ahern and others (1988) linked gradient analysis and spectral data to predict forest species distributions in the North Cascades Mountains in Washington, U.S.A. Ohmann (1996) demonstrates how regional plot data can be linked to environmental gradients derived from climate models and digital maps to derive information relevant to forest planning and policy. Ohmann and Spies (1998) used the above methods to identify regional gradients from extensive field data to characterize woody species composition in Oregon. They were able to develop a conceptual model of species environment relations at the regional scale, which in conjunction with remote sensing can be used to accurately map forest species.

5.2.1.1. The vegetation triplet and the LANDFIRE project

Keane and co-workers (2001) suggested using three indirect layers (called the *vegetation triplet*) integrated with remote sensing data, to map fuels across multiple scales (Keane et al. 1998b, 2000):

- Biophysical settings;
- Species composition;
- Vertical stand structure.

Fuel characteristics can then be assigned to biophysical and vegetation category combinations to create robust and flexible maps for fire growth prediction. As specified in the previous paragraph, biophysical settings are the important environmental factors that govern fuel and vegetation dynamics. Although they provide a context in which to interpret, constrain, or stratify spatial fuel differences (Keane et al., 1997; Lunetta et al., 1998), biophysical settings are inherently difficult to map because they represent the complex integration of long-term climatic interactions with vegetation, soils, fauna, and disturbance (Barrett and Arno, 1993; Keane et al., 1996b). Therefore, many mapping activity use potential vegetation type (PVT), which provide an ideal linkage between biophysical settings and vegetation (Daubenmire, 1966; Pfister et al., 1977). The PVT classification represents the plant community that would inhabit a site in the absence of disturbance, hence uniquely describes environmental conditions.

In literature, PVT classifications have included several and different environmental conditions, as habitat types at fine scale (e.g. Pfister et al., 1977), fire groups at mid-scales (Fischer and Bradley, 1987), or temperature-moisture classes at coarse scales (Reid et al., 1995; Quigley et al., 1996). Terrain modeling is often used to map potential vegetation types from ranges of elevation, slope, aspect, and soils (Deitschman, 1973; Shasby et al., 1981; Barrett and Arno, 1993; Keane et al., 1998b, 2000), since simple biophysical settings maps may be developed from topographic rule-based terrain.

Vegetation composition and stand structure are probably the two most important ecosystem characteristics useful to fuel mapping. Composition is important because the plant species that dominate a community have unique morphology, which is important for fuel mapping also because dead woody debris and litter are directly related to the dominant tree species found on the site (Keane et al., 2000). Finally, the vertical stand structure refers to the current canopy structure of a site, describing the vertical arrangement of live and dead biomass above the ground (O'Hara et al., 1996). This triplet approach has been used also to assess the hazard on forest disease and vulnerability to fire in the Columbia basin (Hessburg et al., 2000) and to mapping fuel in the Moscow Mountain, Idaho (Falkowski et al., 2005).

Actually, this approach was extensively used in the LANDFIRE Prototype Project (Rollins et al., 2004), designed specifically to provide the spatial data required to implement the National Fire Plan at regional levels and to fill critical knowledge gaps in wildland fire management planning. The LANDFIRE Prototype Project integrates information from extensive field-referenced databases, remote sensing, ecosystem simulation, and biophysical modeling to create maps of wildland fuel and fire regime condition class across the United States (Rollins et al., 2004). The main effort of the LANDFIRE Prototype Project approach included the development of a standardized, repeatable method to built comprehensive fuel and fire regime, and provides a robust, statistical framework and quantitative accuracy assessment. Many interrelated and mutually dependent tasks had to be completed to create the suite of databases, data layers, and models needed to develop scientifically credible, comprehensive, and accurate maps of fuel and fire regimes (Figure 21). The LANDFIRE mapping processes began with the creation of the LANDFIRE reference database, which is comprised of a set of all available georeferenced plot information, ground-based databases from both government and non-government sources, from within each mapping zone. The reference and spatial databases were used in a classification and regression tree-based machine learning framework, with the help of ecological simulation, Landsat imagery, and statistical landscape modeling at 30-meter pixel resolution, for creating maps of biophysical settings (potential vegetation types), existing vegetation composition (cover type), and vegetation structure (canopy height and density). These core vegetation maps formed the foundation for the simulation of historical fire regimes and the subsequent calculation of current departure from historical vegetation conditions. These simulations served to quantify both the historical reference conditions and the range and variation of fire regime characteristics critical for determining current departure from historical conditions. Fourth, wildland fuel characteristics were then mapped using field-referenced data, biophysical data, Landsat imagery, and LANDFIRE vegetation products, for eventual simulation of fire behaviour and effects (Figure 22).

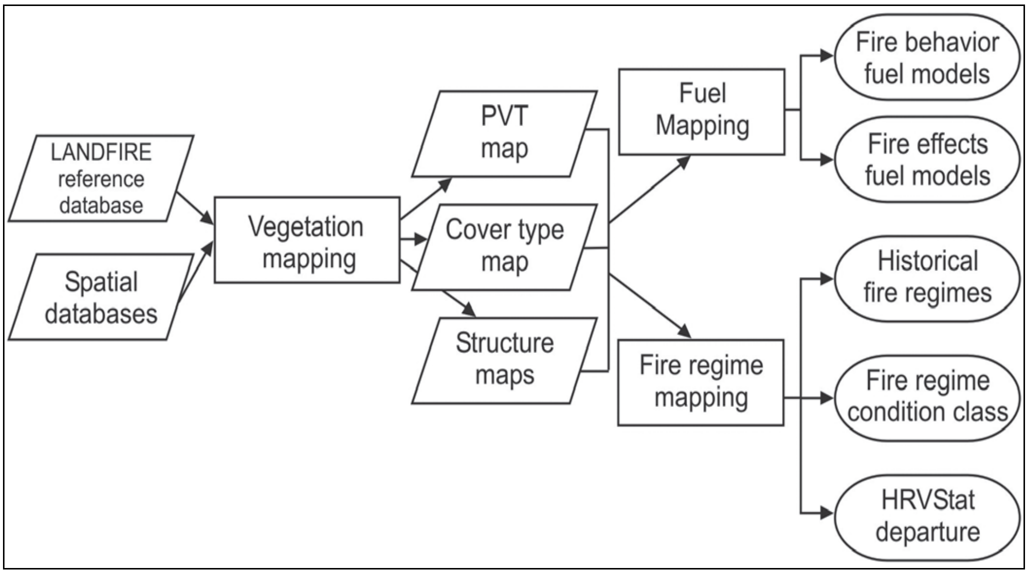


Figure 21. An overview of the LANDFIRE Prototype Project procedures (from Rollins and Frame, 2006)

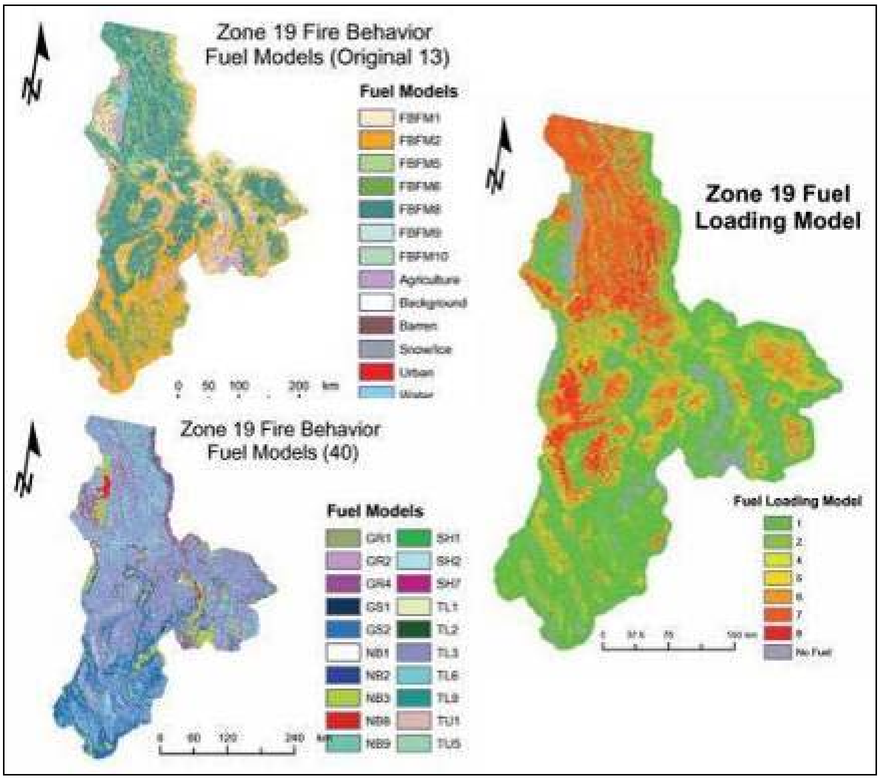


Figure 22. Northen Rockies mountain study area (zone 19) surface fuel maps. Surface fuel model maps for a) the Anderson (1982) 13 standard fire behaviour fuel models (FBFM13), b) Scott and Burgan (2005) 40 fire behaviour fuel models (FBFM40), and c) the default fuel characterization classes (default FCCs)
(from Rollins and Frame, 2006)

5.2.2. FCCS-Fuels Characteristic Classification System

The Fuel Characteristic Classification System (FCCS) developed by the Fire and Environmental Research Application Team (FERA) of the USDA Forest Service, is a sophisticated and comprehensive software system designed to predict potential fire behaviour and to assess fuelbeds from the ground fuel stratum to the canopy (see paragraph 2.2.2).

This program lets the user create a fuelbed based on the published literature or knowledge gained from working in an area for many years and applies these characteristics to a specific landscape.

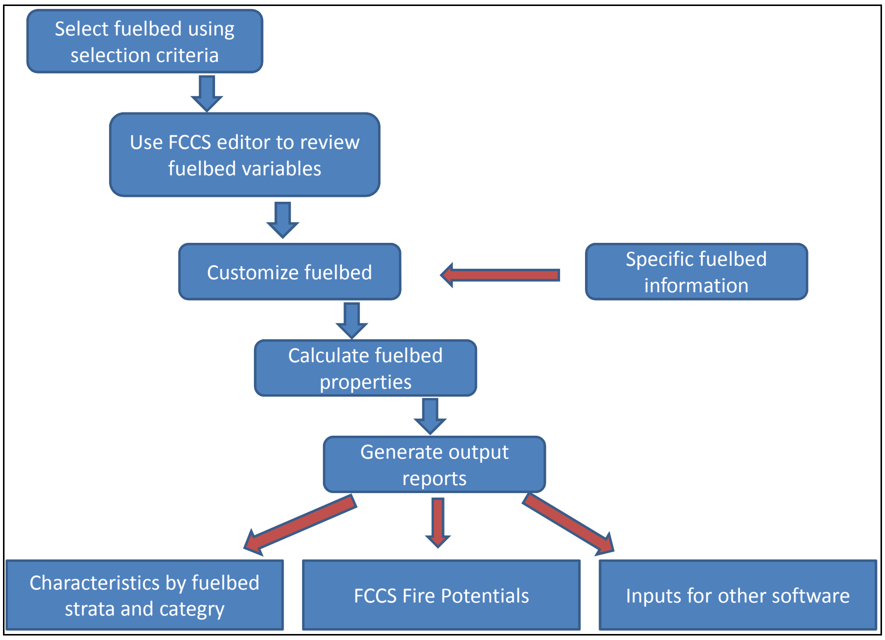


Figure 23. Information flow for the Fuel Characteristic Classification System (modified from Ottmar et al., 2007)

The FCCS is designed to provide quantitative fuelbed information for fire effects models and to assist in building customized fuel models for national application in the United States (Ottmar et al. 2007). Selecting the fuelbed that best represents the combustion environments, through the classification criteria in Table 19, the System provides the best available predictions of the information associated with every single fuel strata, allowing the computation of fuel characteristics.

Table 19. Selection classification criteria for the Fuel Characteristic Classification System (FCCS) fuelbeds.

Criterion	Description	Source
Ecoregion division		*Bailey (1997)*
Vegetation form	describes the gross physiognomic structure of a landscape unit	*Grossman et al. (1998)*
Structural class	applies mainly to forests and captures the number of canopy layers, relative size of trees, stage of understory, and relative degree of stand closure	*adapted from Oliver and Larson (1996)*
Cover type	based on dominant vegetation using forest cover types of the United States	*Eyre (1980) and Shiflet (1994)*
Change agent	refers to activities that significantly alter fuelbeds	
Natural fire regime	describe the role fire would play across a landscape in the absence of human intervention	*www.frcc.gov*

With these estimates the System calculates all the parameters required as inputs by fire models, and probable fire parameters specific to the fuelbed in question. In effect, to avoid several problems that the continuous fuel characteristics generation creates, as the limitation to the different fuelbed comparison, or the continue calibration to generate appropriate model behaviour (Sandberg et al., 2001), the System includes three key fire parameter, allowing every fuel to be defined into characteristic classes (Figure 24):

– Index of potential spread rate or reaction intensity;
– Index of crowning potential;
– Index of fire effects based on biomass consumption;

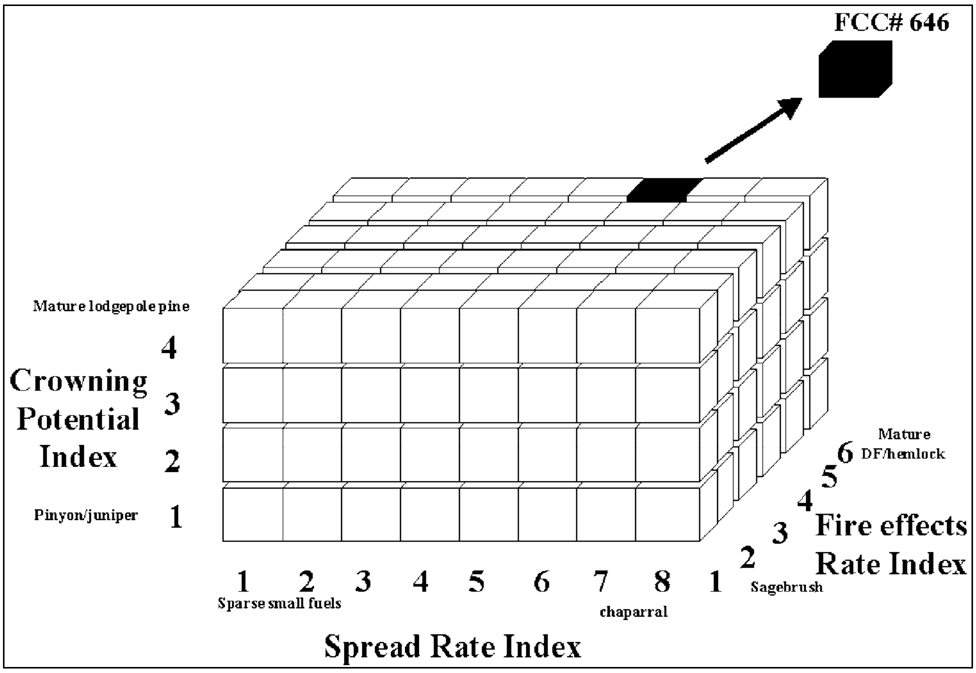


Figure 24. Fuel characteristic classes grouped by three critical attributes of spread rate, crowning potential, and fire effects (from Sandberg et al., 2001)

The major FCCS outputs are:

– Fuelbed characteristics, including percent cover, depth, height, height to live crown, percent live foliar moisture content, density, diameter at breast height, loading live, loading dead, fuel area index, packing ratio, and optimum packing ratio. The FCCS calculates and reports these characteristics fore each fuelbed stratum, category and subcategory (Riccardi et al. 2007*b*);
– FCCS fire potential, a set of relative values that rate the intrinsic physical capacity of a wildland fuelbed to support a surface fire at benchmark conditions (Sandberg et al. 2007*a*, 2007*b*), support a crown fire (Shaalf et al. 2007), and to provide fuels for flaming, smoldering, and residual consumption (Sandberg et al. 2007*a*).

5.2.3. European approaches to mapping fuels

In Europe, fuel-type maps only exist at a national level and do not allow any intercomparison of types because of the lack of homogeneity in the classification of the fuel types across countries (Sebastián-López et al., 2002). For this reason a pan European fuel-type map was developed through the intersection of the CORINE

Land Cover (CLC) and the "Natural Vegetation Map of Europe" (Sebastián-López et al., 2002). As a first approach, a fuel model map was developed through the intersection of the CORINE Land Cover (CLC) (Corine Land Cover, Technical Guide, 1994) and the "Natural Vegetation Map of Europe". This map is a mixture of actual and potential vegetation, which recognizes over 100 vegetation associations at 1:300,000 scale (Eurostat, 1999). The CLC was used to mask out agricultural and non-vegetated land, classified as 'no fuel', and to retain only the CORINE class of interest (Table 20), to stratify the area before assigning the fuel types.

Table 20. CLC codes used in the construction of the fuel map (Sebastián-López et al., 2000).

CORINE code	*Description*
2.3.1	Permanent grasslands
2.4.3	Land principally occupied by agriculture, with significant areas of natural vegetation
2.4.4	Agroforestry areas
3.1.1	Broad-leaved forest
3.1.2	Coniferous forest
3.1.3	Mixed forest
3.2.1	Natural grasslands
3.2.2	Moors and heathland
3.3.2	Sclerophyllous vegetation
3.2.4	Transitional woodland-scrub
3.3.3	Sparsely vegetated areas
4.1.2	Peat bogs
4.2.1	Salt marshes

The intersection of CLC classes with the vegetation map resulted in small homogeneous regions and each region was assigned a particular fuel type, with the help of the NFDRS Fuel Model Key (Deeming et al., 1977) which classifies the fuels according to the type of understory vegetation that would spread the fire once started (mosses, marshes, grasses, brushes, or trees). The authors affirm that the fuel models were assigned through a phytosociological approach (Sebastián-López et al., 2000), since the climatic characteristics of each region, the soil type, the topography, underlay the differentiation of the associations in the vegetation map, determine how the different species spread. The result is a fuel type oriented vegetation map (Figure 25).

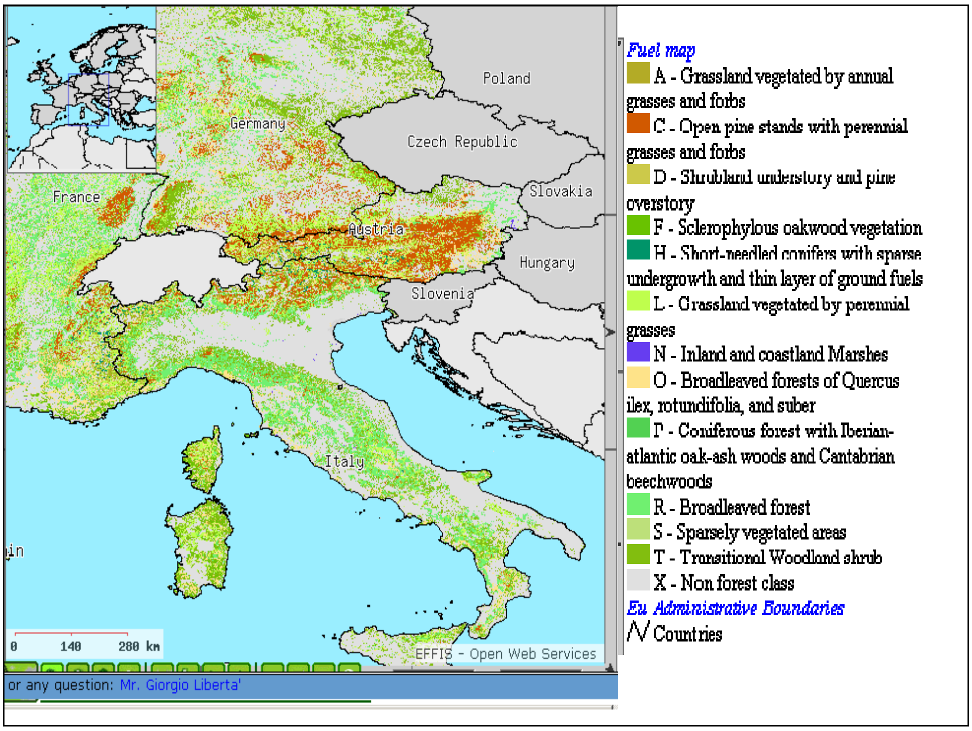


Figure 25. Fuel type Map (from http://effis.jrc.ec.europa.eu)

Another methodology that is now being explored in Spain and in Greece, in particular, is the object oriented classification. Although this method emerged as early as the 1970s (Ketting and Landgrebe, 1976), object-based analysis was not used extensively in the remote sensing field (Flanders et al., 2003; Laliberte, et al 2004; Ivitis et al., 2005). These techniques take into account not only the spectral characteristics of a single pixel but those of the surrounding (contextual) pixels in the image segmentation phase. The results are the creation of image objects defined as individual areas with shape and spectral homogeneity (Jensen, 2005). In many instances, carefully extracted image objects can provide a greater number of meaningful features for image classification (Visual Learning Systems, 2002). In addition, objects don't have to be derived from just image data but can also be developed from any spatially distributed variable (e.g., elevation, slope, aspect, population density). Homogeneous image objects are then analyzed using traditional classification algorithms (e.g., nearest-neighbor, minimum distance, maximum likelihood) or knowledge-based approaches and fuzzy classification (Jensen, 2005). This classification method recognizes that important information is not represented in single pixels but in meaningful objects in an image and their mutual relations, (http://charlotte.utdallas.edu). Object-oriented classification software assumes that related pixels are actually part of objects, and assigns properties and relationships to the whole object rather than individual pixels (Wikipedia, 2005). The algorithms behind this classification method utilize spectral, spatial, texture, shape, context and ancillary information to model the feature extraction process. Giakoumakis and others (2002) used this method to develop fuel maps with a satisfactory result. Two Object-Oriented Models for fuel type mapping based on the PROMETHEUS fuel type classification system (see chapter 2.2.) were created, one from Landsat TM and IKONOS images, to determine how the PROMETHEUS system could be detected via Remote Sensing in the case of a medium-high (Landsat) and very high (IKONOS) resolution images, and evaluate the results (Giakoumakis et al., 2002). Figure 26 illustrates the steps used to standardize processing with the aim to obtain two thematic maps.

The Landsat satellite image provides enough information to be able to recognize the main classes (water, bare land, shrubs and forest) and the subclasses (coniferous, broad leaved trees, etc.), but not enough information about the shape and texture of single objects. IKONOS can provide the information necessary to recognize individual objects, detect texture differences among them, and irregularities in the areas under investigation (Giakoumakis et al., 2002). This method adopts not only the spectral signature methodology but also some spatial characteristics – such as shape, texture and neighboring objects – were taken as the main classification factors. But, due to the poor spectral information, often different classes with similar reflectance required efforts to be distinguished, and due to the very high resolution often unnecessary data were included in the unclassified data, reducing the accuracy.

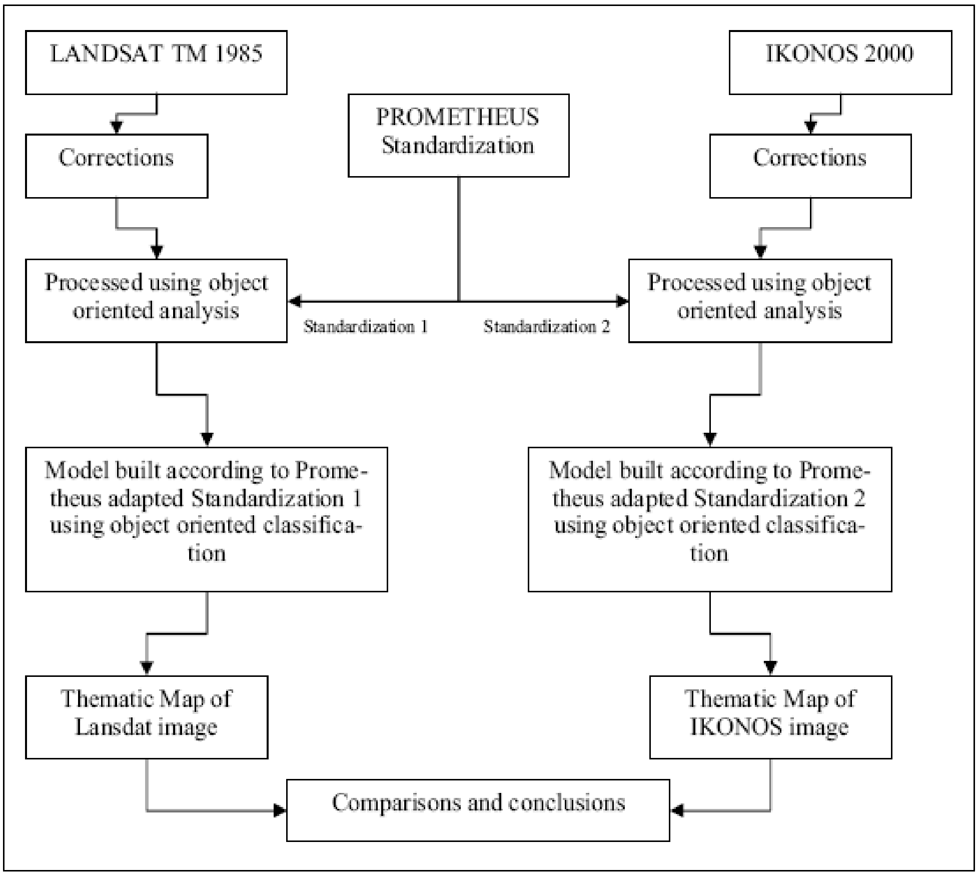


Figure 26. Methodology structure diagram (from Giakoumakis et al., 2002)

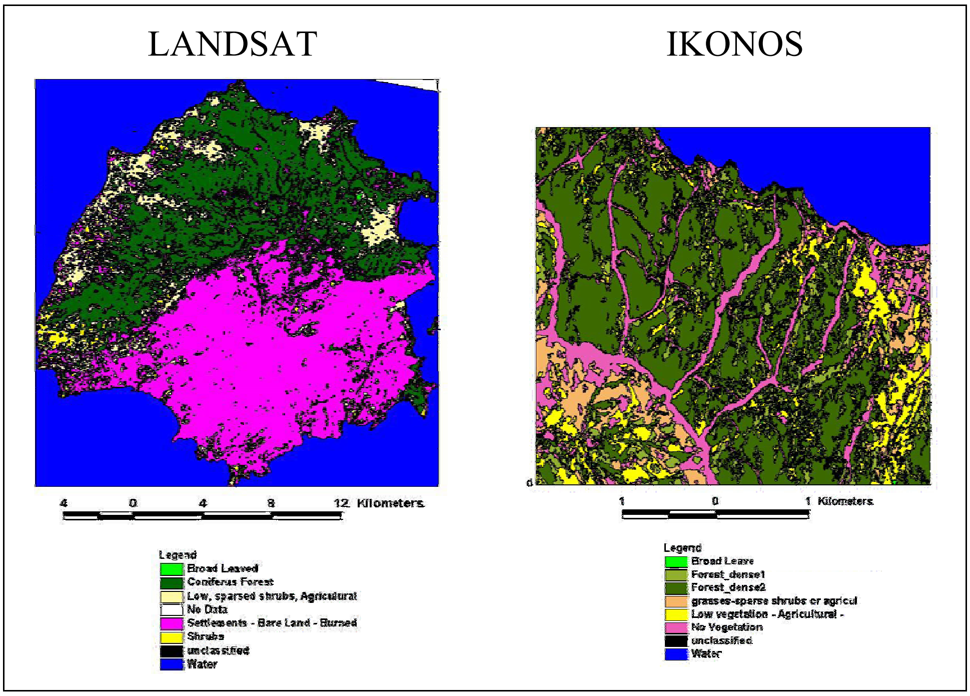


Figure 27. Landsat and IKONOS Thematic Map of study area (adapted from Giakoumakis et al., 2002)

6. OBJECTIVES

As emphasized in the previous chapters, the availability of accurate spatial data on vegetation characteristics and fuel models finds remarkable importance in several topics of fire prevention and management, such as the development of fire risk maps, the study of the fire behaviour and propagation, the activities of fuel management in prescribed fire, the analysis of the emissions, and the polluting effects of the smoke. In addition, other environmental applications (e.g. regional carbon dynamics, smoke scenarios, and biogeochemical cycles) (Running et al. 1989; Kasischke et al. 1998; Leenhouts 1998; Lenihan et al. 1998) may benefit from the development of specific themes useful to quantify the different pools of plant biomass and necromass.

In Europe, on the wake of the advance in these topics reached essentially by the United States, several efforts were made in order to characterize the fuel and to develop a set of fuel models, including the Mediterranean vegetation. Some of these attempts (e.g ICONA, 1990) simply assigned the NFFL fuel model after a visual characterization of the fuel complexes. Several research studies, carried out in Portugal and Greece investigated on the properties of fuel particles and fuel beds for a broad range of species and cover types of Mediterranean vegetation (Fernandes et al., 2006)

In Italy, there is a lack of studies focused on a systematic analysis of the vegetation characteristics related to fire behaviour, as listed in the introduction. From the 2001, a field survey of several vegetation attributes (e.g. number and diameter of woody plant distinct in species, diametric growing and height of sample trees, stump dimension and dead downed, entity and composition of the understory) was conducted within the new Italian National Forest Inventory (IFNC, Ministerial Decree, 2001). However, information and data on chemical and physical characteristics of the different standard size classes useful for the development of fuel models and for the estimation of potential fire behaviour were not included in the Inventory. On the other hand, the use of fuel models developed in other countries without a prior calibration is controversial (Zhou et al., 2005a;

2005b). Inaccuracies of fuel models affect the performance and realistic predictions of potential fire behaviour models and simulators.

In this work, is proposed an integrated approach based on general field data collection, and fuel classification and mapping is presented. The main objective is to provide a set of fuel models for the main Mediterranean maquis associations. The specific aims of the work are: (i) to characterize the fuel complexes, (ii) to analyze the relationship between fuel complex properties and fuel load, (iii) to develop a set of fuel models for Mediterranean maquis, (iv) to develop maps of fuel models at local scale using satellite imagery, and finally (iv) to evaluate the capabilities of fuel model and map themes to simulate the fire spread and behaviour using spatially and temporal explicit fire simulators.

7. MATERIALS AND METHODS

7.1. Experimental area

The case study is represented by the North-West territory of Sardinia Island (Italy) (Figure 28) the second largest island in the Mediterranean. Sardinia it measures 24,090 km^2 and is located between 38° 51' 52" and 41° 15' 42 " North latitude and 8° 8' and 9° 50' East longitude. The coasts of Sardinia (1,849 km long) are generally high and rocky, rectilinear for kilometers, they are often articulated in promontories, with ample and deep bays and inlets surrounded by smaller isles. Sardinia is an ancient territory with rocks that go back to the Ancient Paleozoic (300,000 years ago), and does not possess any high mountain because of its long history of erosion. Granite, schist, trachite, basalt, sandstone, dolomie-limestones rocky highlands predominate with heights between 300 and 1,000 meters.

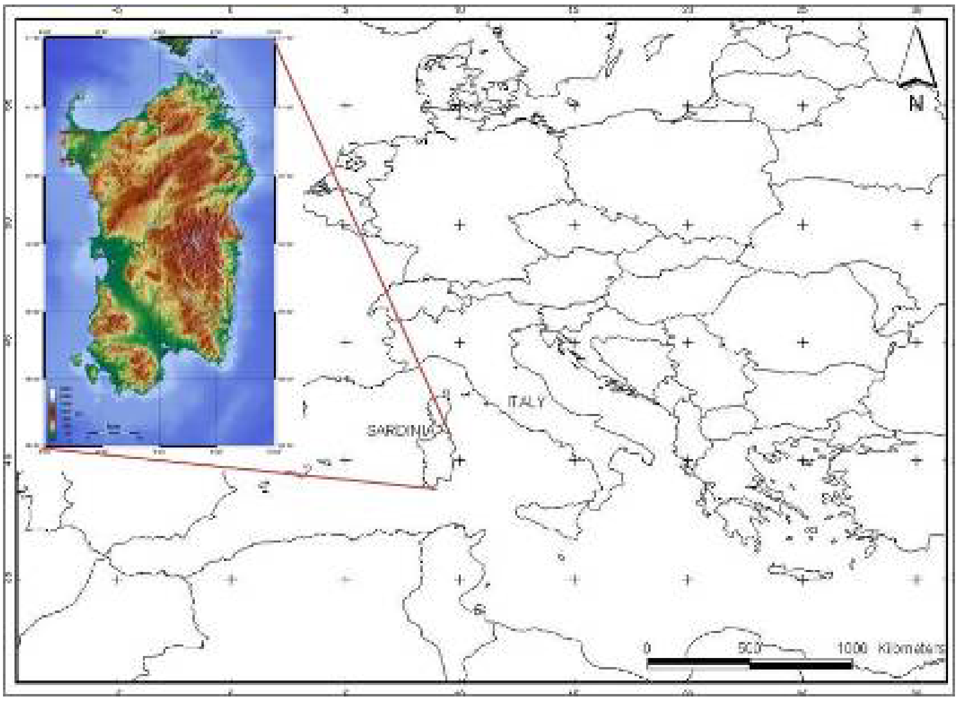


Figure 28. Geographical map of occidental Mediterranean basin. With the red quadrat the case study area is evidenced

The climate is sub-arid with a remarkable water deficit from May to September, and most annual rainfall (approximately 700 mm, Figure 29a) occurs in fall and winter. During the summer season, the cumulative amount of precipitation is very limited (Figure 29b). The mean annual temperature along the coast line is approximately 18 °C (Figure 29c) with peaks higher than 30 °C in summer season (Figure 29d).

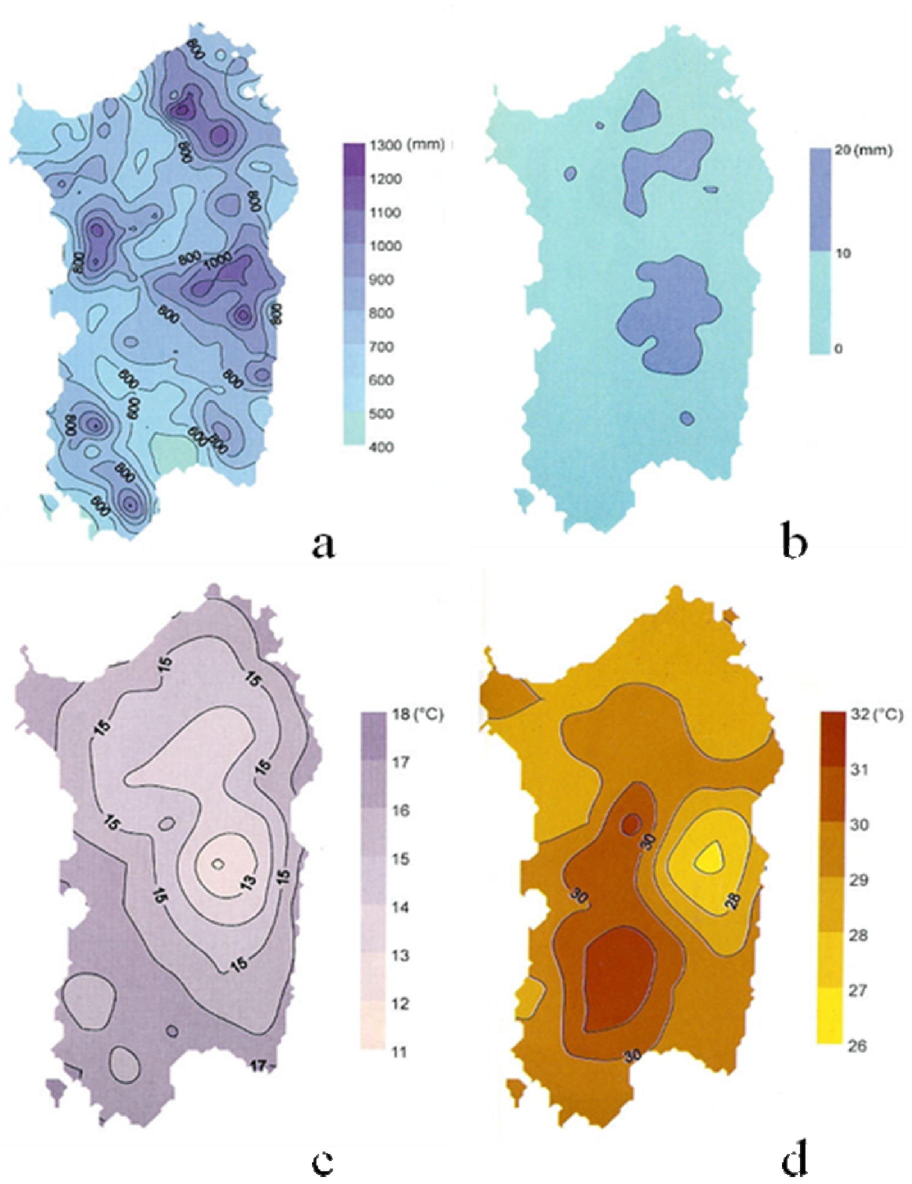


Figure 29. a) Sardinian annual cumulative amounts of precipitations; b) Sardinian cumulative amount of precipitations (in July); c) Sardinian mean annual temperatures; d) Sardinian mean maximum August temperatures (Chessa and Delitala, 1997)

The main land use of the Island is agriculture (Figure 30). It is interesting that the percentage of the areas suitable to the agriculture, including crops, sown field and orchards, accounts for 38% of the whole area, while similarly shrubs and herbaceous associations contribute to 36%. In this shrub category (more than 8,500 km^2), there are several vegetational associations, ranging from natural pasture (32%) (that is forage areas in less productive zone such as surfacing rock), scrubby and shrubby areas (composed of vegetational formation very dense or low riparian formations), Mediterranean maquis (38%), garrigue, and natural and artificial re-colonization areas (Figure 31).

The experimental activity was concentrated in the North West of Sardinia Island, falling mainly in the Nurra district, because of the extending of Mediterranean maquis (about 61 km^2) (Figure 32). This study connects within a wider project with the purpose of map the fuel in all the North Sardinia.

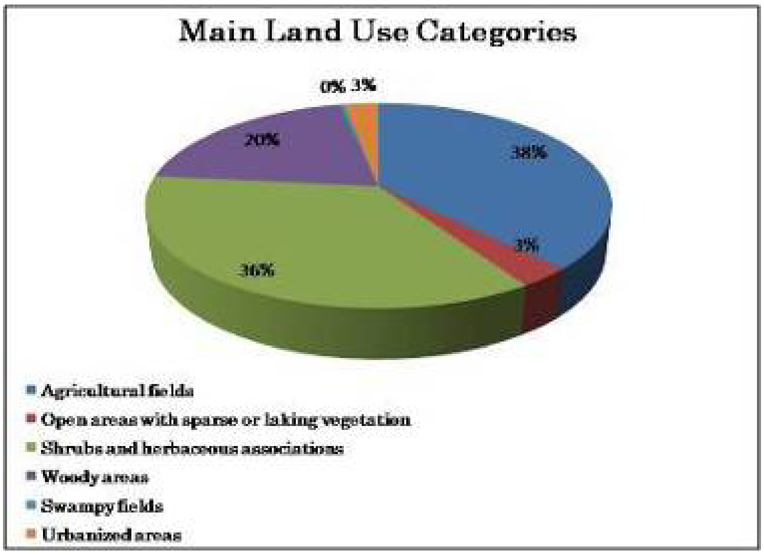


Figure 30. Main land use categories from CORINE land cover (2000)

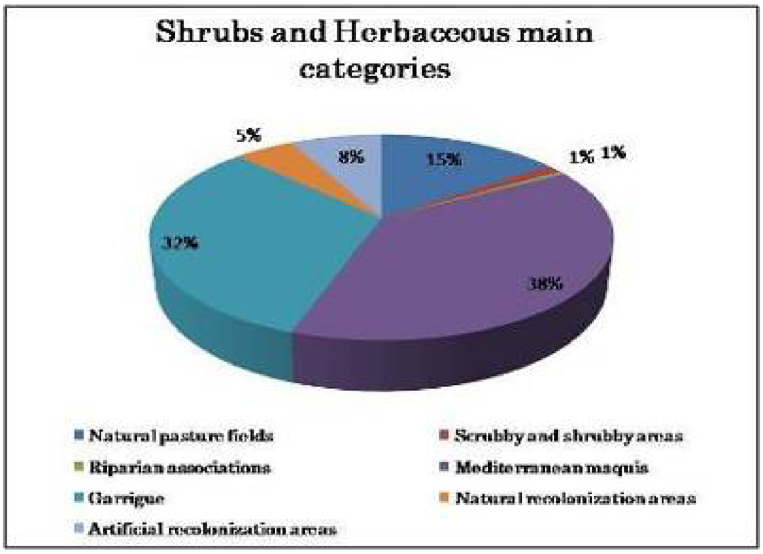


Figure 31. Shrubs and herbaceous classes from CORINE land cover (2000)

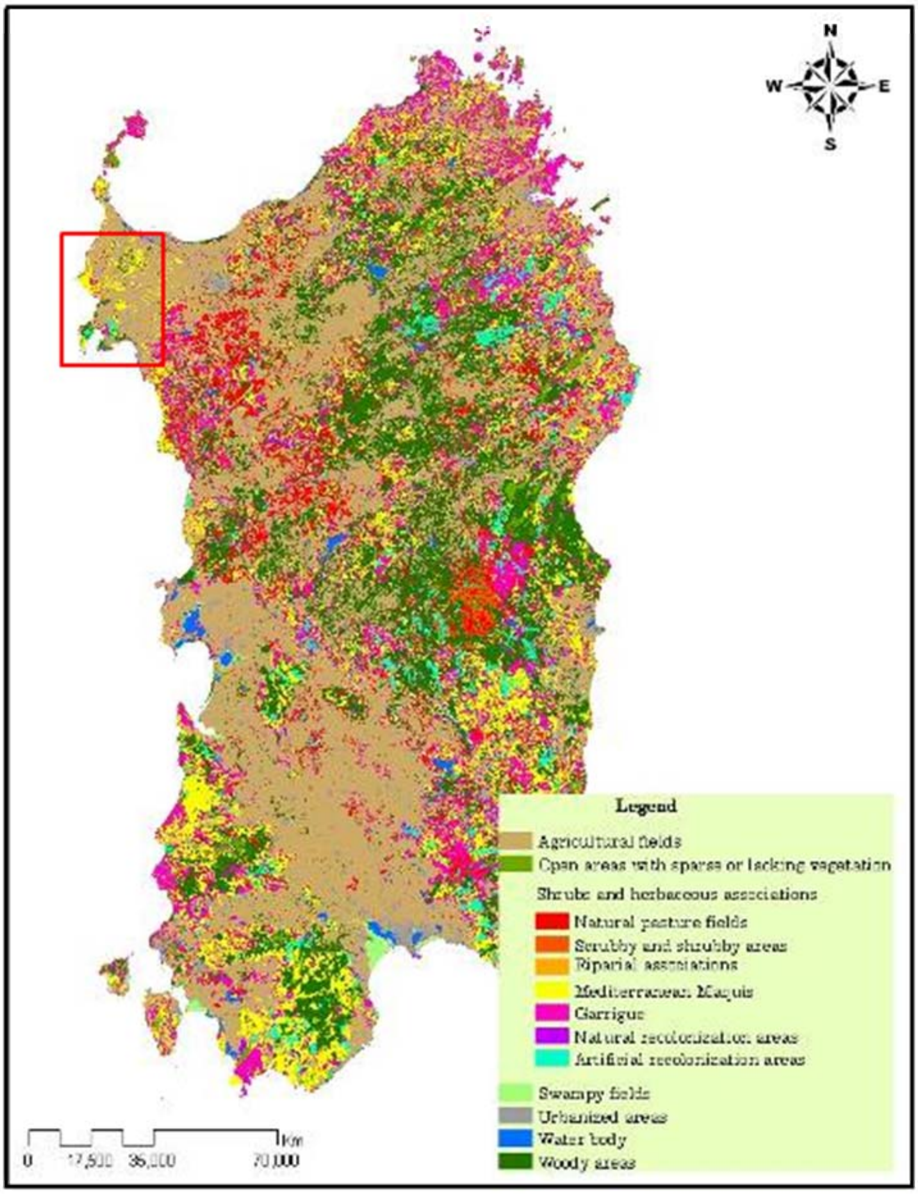


Figure 32. Map of main land use categories, from CORINE land cover (2000). The red rectangle localize the sampling area

7.2. Sampling scheme

It is well known that the Mediterranean maquis of Sardinia includes several vegetational associations at different successional stages influencing the spatial homogeneity of the vegetation and the landscape (Figure 32). Thus, the selection of several sites sufficiently extensive and characterized by homogeneous cover is not easy. In these conditions, sampling schemes, such as stratification, typically used in forestry resources studies, are not easily applied. Therefore, several vegetated areas have been identified, to represent maquis areas affected by the disturbance factors considered in this study, with a particular regard for fires. These areas are characterized also by a mosaic of vegetational typologies, most of them herbaceous type, and tightly connected with agricultural exploitation.

To locate these areas, Mediterranean maquis areas were identified by the Land Use Map Corine Land Cover (2000), the analysis of orthophotos, previously mosaiced, and satellite images. A grid of regular form and constant dimension (100 ha) was overlaid above the orthophotos, and a random sample of points were extracted in ArcGIS (ArcGis 9, ESRI Inc., Redlands, CA, USA) through specific tools on the layer corresponding to Mediterranean maquis areas (Figure 33).

The extracted points have been evaluated in terms of suitability for one or more test areas, verifying the extent and density of the shrubby cover. According with the decree 227/2001 and with the new Prescription for the Forest Police (PMPF), issued in September 2006, the Mediterranean maquis is wood and is characterized by a precise area extent, width and a well defined cover: it must have 2000 m^2, 20 m minimal width and cover of 20% in decree 227/2001; over 50% (unless for the coastal juniper' stands) in the PMPF.

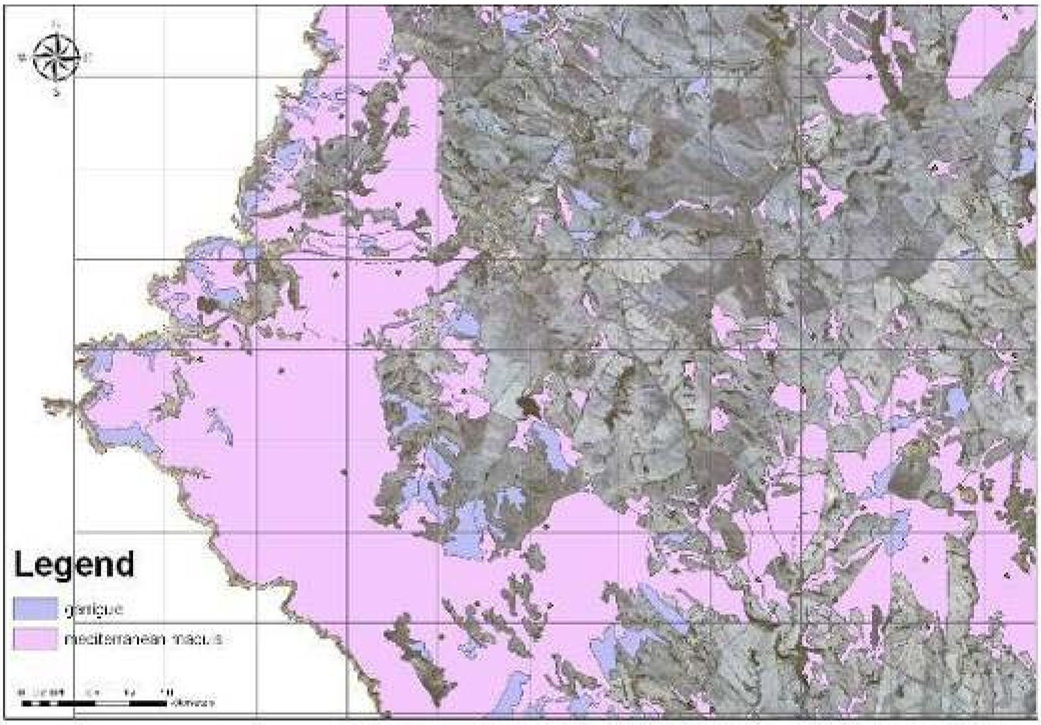


Figure 33. The grid of regular form and constant dimension and the point's population

To estimate the extent and density of shrubby cover, informative layers were analyzed, with the photo-interpretation of mosaiced orthophotos and a defined graphical object. This object is known as the "round of analysis" (Figure 34), defined by a quadrilateral composed of 9 contiguous squares with 50 m side. A 10x10 m point grid was associated to each square. This "round of analysis" effectively estimates the degree of cover and verifies the overcoming of fixed thresholds (INFC, 2003b). Always it has been verified that:

– the polygon, to which the random extracted point belongs, exceeds the critical threshold of 5000 m^2;
– the cover exceeds the threshold of 20%.

The whole experimental area sites is located in the Nurra and Sassarese sub-region, within an area of 382 km^2, of which about 61 km^2 is Mediterranean maquis, from the village of La Corte (SS), crossing the Monte Forte area, till the coastal area of Argentiera (Table 21).

Figure 34. The graphical object "round of analysis" and the associated point's grid

Table 21. Exerimental area coordinates

Area	CODE	n° plot	Latitude	Longitude	Year since last fire
1 La Corte 1	LC1	5	4510357	1438686	
2 La Corte 2	LC2	5	4506178	1446496	2
3 La Corte 3	LC3	5	4509944	1443555	3
4 Porto Palmas	PP	5	4511445	1429830	8
5 Rumanedda	RU	5	4503060	1445210	
6 Monte Doglia 1	MD1	5	4497925	1434395	2
7 Monte Doglia 2	MD2	5	4497977	1434424	
8 Monte Forte	MF	5	4507262	1438786	27

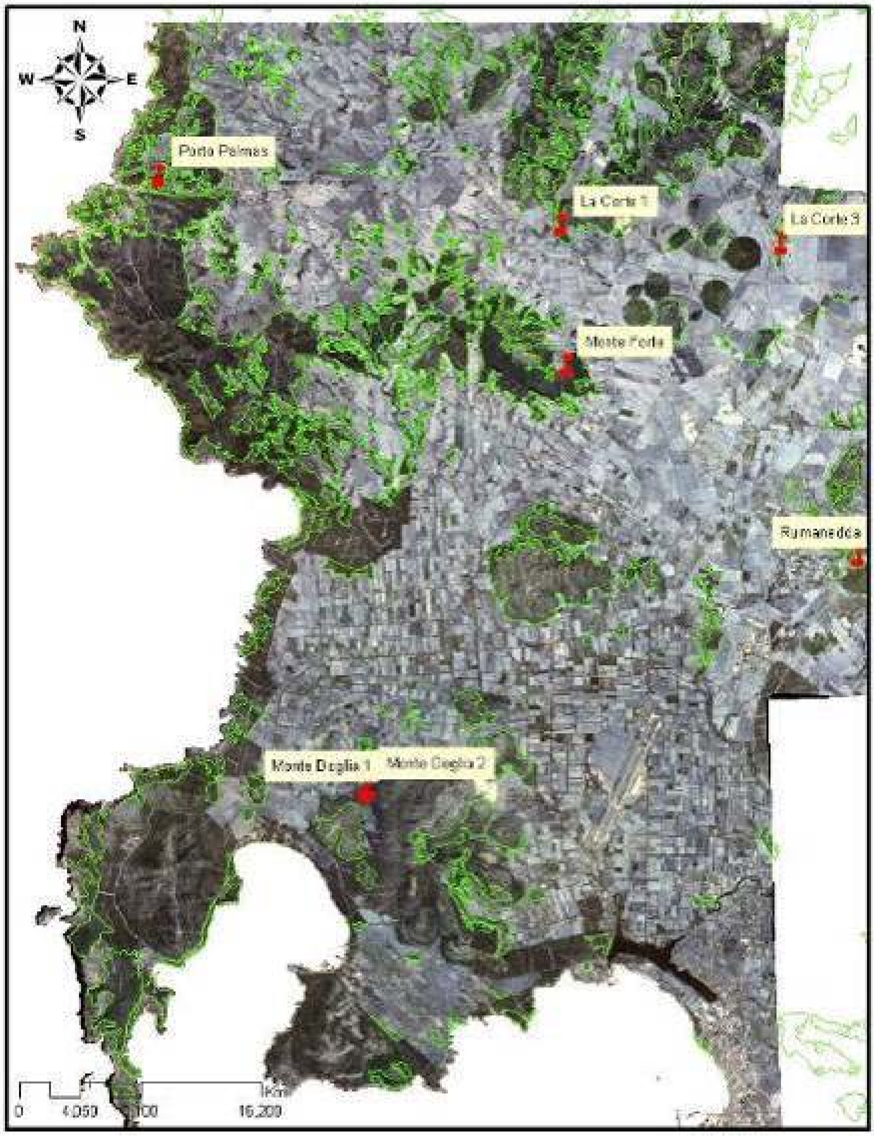


Figure 35. Experimental sites localizations. The green line indicate the limits of Mediterranean maquis

The sampling probabilistic scheme proposed for the ground survey of the fuel main attributes is cluster sampling (Corona, 2000). In the cluster sampling, the population is partitioned into primary units, each one composed of secondary units. In particular, in cluster sampling, a primary unit consists of a cluster of secondary sampling units, usually in close proximity to each other. Cluster primary units include such spatial arrangements as square collections of adjacent plots or long, narrow strips of adjacent units.

In this study, the cluster primary unit was supported by five secondary units, called *plots*, (2x2 m) constituted by sampling areas displaced across two linear transect disposed orthogonally (Figure 36). The orthogonal disposition of the transects permits sampling along two orthogonal guides avoiding the possible estimate's bias due to topographic pattern. The transect length may vary according to several factors, including the minimum size of the sampling area, environmental characteristics. In this study the transect length was 30 m.

The following variables were measured and collected on each plot: fuel load, depth of the fuel layer, and plant cover. A line interception method was used along the linear transects, to survey the species composition and the height of plants (see § 4.2.3) (Stahl et al., 2000).

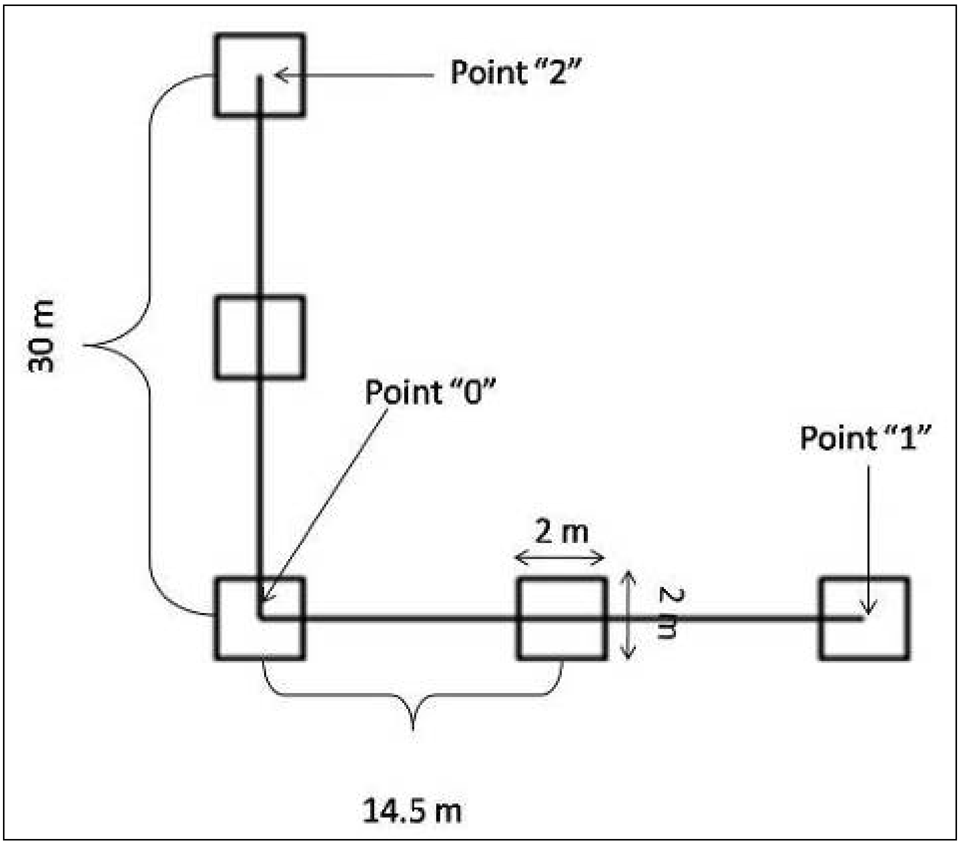


Figure 36. Cluster sampling scheme

7.3. Fuel data collection

The experimental survey was carried out between June 2007 and August 2008. Firstly, in every test area, the characterization of the site included locality and geographic coordinates, and several other descriptors (Table 22).

Table 22. Main descriptors characterizing the test area

Descriptors	*Characteristics*
Vegetation	Height
	Cover
Trees	Dominant species
	Height
	Cover
	Diameter at breast height
Shrubs	Dominant species
	Height
	Cover
Herbaceous	Dominant species
	Height
	Cover
Fire	Year since last fire
	Fire intensity

Subsequently, the transects and the relative plots were built. Transects were set up from the sampling point identifying the sampling area (point 0, Figure 36), and disposed orthogonally, such as the L, stretching carefully a measuring tape to 30 m. The final transect points were recorded with a GPS (Global Positioning System) in Gauss-Boaga coordinates, and called point 1 and point 2 (Figure 36). The measuring tape was stretched taut and straight above the vegetation canopy. Along the transects, five plots (2x2 m) were placed, at equal distance of 14.5 m to each other. Their centres were recorded with the GPS, and the boundaries were defined with tape (Figure 37). Next, shrubs, herbaceous, downed woody material, litter fuel strata were surveyed. For every phase several forms were developed (Appendix 1,2, and 3).

Figure 37. The sampling plot

7.3.1. Data collection along the transect

Plant *cover* was sampled by the line intercept method, in which the length of intercept for each plant species was measured along a tape by recording the point on the tape where the plant canopy begins and the plant canopy ends. The intercept lengths were summed and divided by the total tape length in order to calculate the value of percent cover for each plant species. Plant *height* was collected along transects by measuring the vertical distance from the soil surface to the top of the branches. Measurements were performed every 10 cm.

7.3.2. Data collection in the sampling plot

For each sampling plot, several digital photos were collected by placing a digital camera with remote control perpendicular to the ground at about two meters above the plants. The images were imported and analysed using AutoCAD map 2002 (Autodesk Inc.) in order to calculate the area covered by each species; the perimeter of the plot was digitized, as the perimeter of every species of the plot, and the cover area was then computed (Figure 38).

Plant *height* was measured, within the plot subdivided into 16 quadrants, as the vertical average distance from the soil surface to the top of the branches of the predominant species of each quadrants (Figure 39).

Figure 38. A digital photos analyzed with AutoCAD (2002)

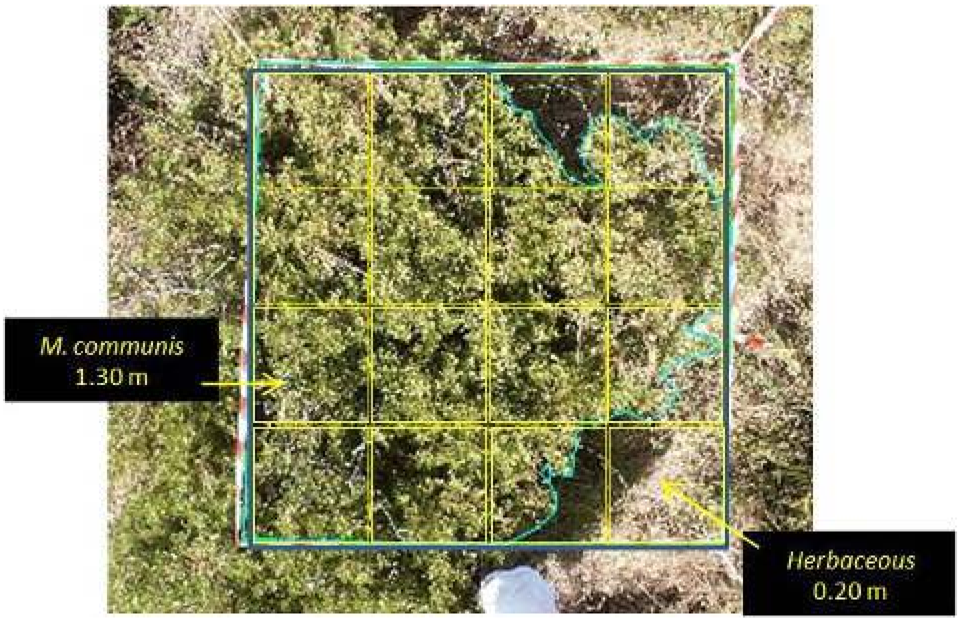


Figure 39. Species and heights in the 16 plot's quadrants

Shrub biomass and necromass were inventoried on the selected sample plots by cutting the stems at ground-line. The different materials were weighted using a digital dynamometer (KERN & SOHN GmbH, Balingen-Frommern, Germany) with a weigthing range max. of 10 kg and an accuracy of 10 g. A sample of about the 20% of each sample was collected for the subsequently laboratory analysis. The litter was sampled by dividing the plot in four quadrats and collecting a sample for each quadrat using a 0.13x0.13 m sampling frame (Figure 40).

Figure 40. Small quadrats to collect the litter

The equilibrium fuel moisture time-lag size classes (Fosberg, 1970; Rothermel, 1972) were used at the laboratory in order to separate the plant material of each species into the following size classes, using the values of the steam diameter: 0 to 0.6 cm (fine fuels), 0.6 to 2.5 cm (medium branches), and 2.5 to 7.5 cm (thick branches) (Figure 41). The size groups given here correspond to the 1h-, 10h, and 100h time-lag fuels described in the literature (Deeming et al., 1972). The fresh loads of each sample were weighed using an electronic balance. A subsample of about 20% was taken and dried in an oven at 102°C for 96 hr, in order to measure the dry weight.

A small sample of leaves and twigs of two of the main representative species (*Cistus monspeliensis* L., *Pistacia lentiscus* L. *Myrtus communis* L.) was collected at the LC1 site, in order to estimate the surface area to volume ratio (SAV, m^{-1}). As mentioned in the introduction section, the SAV ratio is a specie-specific parameter;

therefore, the experimental values were compared with the values provided by several authors for Mediterranean vegetation (Leone et al., 1993; Fernandes, 2001; Baeza et al., 2002; De Luis et al., 2004; Moro, 1997; Pellizzaro et al., 2005), in order to obtain a reasonable value of SAV for each fuel model.

All data acquired during the field survey were stored in a relational data base management system (Microsoft Access, 2002). The database included: at the lowest level the information regarding all the parameters surveyed for every species; at the medium level the information relative to the plot, and at the upper level, the cluster information. Several queries were developed in order to summarize the data at the different levels, to calculate the derived variables, and to export the data for statistical analysis. Finally, several forms and reports were developed in order to control the imported data, and to provide tabular reports of data, summarized by plot and area.

Figure 41. Samples of live and dead fuel, divided in timelag size classes

7.3.3. Statistical analysis

Several statistical tests were applied in order to summarize the data, to account for the effect of disturbances on fuel load, to classify the principal groups of fuel, and to evaluate the goodness of fit of the fuel models.

The data of shrub presence collected along transects were used as inputs in the statistical software STADIV (Ganis, 1991) with the aim to evaluate several ecological index, to define the richness and the diversity between the burned and unburned areas, and within the two groups. Species richness (or species abundance), that is the total number of species present in the area, was computed through the Margalef index (1960), which is an attempt to estimate species richness independently of the sample size. Moreover, in every area the floristic diversity relative to the surveyed shrub species, responsible for the vegetation structure, was quantified with Shannon index (H) (1948). The effective number of species contributing to the diversity, that is the number of species of equal abundance giving the H value, was computed through Hill's number (1973).

The surveyed data were preliminary evaluated using normal Q-Q plots (showing the quantiles of a variable's distribution against the quantiles of the normal distributions) and Levine test of equality of variance to reveal threats to the assumption of normality or homogeneity of variance. Experimental data normally distributed were analyzed for differences between burned and unburned areas by calculating the *t*-Student test. Alternatively, the non parametric Mann-Whitney U test was performed. Finally, one way ANOVA and LSD (Least Significative Difference) test *post hoc* were performed to evaluate the differences within burned and unburned sites. The LSD test was performed to separate the means exclusively when *F*-test of ANOVA reached the significant threshold $p <= 0.05$.

A correlation matrix was set in order to quantify the covariances between several fuel variables (live and dead at 1 hr load, total available shrub load, total shrub load, litter), and the following fuel components: shrub's height, cover, and the product of height and cover, litter height. The analysis was carried out for all the sampling plots, whether recently burned or not. The most significant relationships provided by the correlation matrix were chosen in order to perform the regression analysis and to explain the variance of the different fuel load components by the physical properties of the fuel. For the assessment of the goodness of fit of the models the following statistics were calculated: coefficient of determination (R^2), standard error of estimates (SE), mean square of residuals (MS), F ratio, and F ratio significance. Statistical analyses were performed using Statistica (StatSoft, Tulsa, Ok, USA).

The dataset was subjected to cluster analysis with the aim to identify homogeneous groups in term of both fuel load and fuel characteristics, and to define groups of fuel model. The cluster analysis classifies a set of observations into several mutually exclusive unknown groups based on combinations of interval variables. The term cluster analysis (first used by Tryon, 1939) encompasses a number of different algorithms and methods for grouping objects of similar kind into respective categories. In this work, the Ward's method was used. It is particularly suitable for minimizing the variance within groups, maximizing at the same time the variability between groups. With Ward's method it is possible obtain several homogeneous classes well separated each from the others. The distance used was the Euclidean, the geometric distance in the multidimensional space. It is computed as:

$$dist_{(x,y)} = \left\{ i(x_i - y_i)^2 \right\}^{\frac{1}{2}} \qquad (14)$$

Compact clusters and a *cleanest-looking* dendrogram were performed applying the Ward's method, using the MINITAB trial version (MINITAB Inc.)

7.4. Fire behaviour fuel models

7.4.1. Maquis fuel type development

The average value of plant height and plant cover of all plots grouped by the cluster analysis were then considered and classified according with an adaptation of Prometheus classification system, developed for obtaining a standardization system of maquis properties classification. As referred in § 3.2, the Prometheus classification system considers the shrubs subdivided in: (i) low-lying shrubs, comprising grasslands, low-lying shrubs (30-60- cm high) and a high percentage (30-40%) of herbs; (ii) medium shrubs, comprising medium to large-sized shrubs (0.60-2.0-m high), land coverage can be greater than 50%; (iii) tall shrubs, composed by tall shrubs (>2.0-m high). In this study, the classification system adopted is summarized in Table 23, with the shrub fuel types distinguished in six categories.

Table 23. Maquis type classification system

Height	*Cover*		
	open 0-40 %	medium 40 – 75 %	close 75 -100 %
low < 0.60 m	Low-open	Low-medium	Low-close
medium 0.60 – 1.5 m	Medium-open	Medium	Medium-close
high > 1.5 m	High-open	High-medium	High-close

The clusters identified by this classification were rearranged in order to consider the different typologies of fuel that mainly could express the variability surveyed in the field, also based on the knowledge of the territory.

7.4.2. Maquis custom fuel model development

Fire behaviour fuel models (FBFM) describes the fuel complex that carries fire spread as required by Rothermel's (1972) model. FBFM were conceived of as a set of standardized and stylized inputs for use in fire behaviour prediction across the range of fire spread observed in surface fuels. Stylized fuel models were meant to approximately represent fuelbed properties found in nature. Each fuel model is a small database of fuel properties, whose values determine its expected potential fire behaviour, described mainly by:

- the fuel load for each required size class;
- the ratio of surface area to volume;
- the depth of the fuel bed involved in the fire front;
- the fuel moistures, including that at which fire will not spread, called the moisture of extinction;
- the fuel heat content (live and dead).

BehavePlus 3.0 permits to evaluate the desiderated range of potential fire behaviour of a fuel model, using as input data the fuel values of each model. The BEHAVE (Andrews, 1986; Andrews and Chase, 1989; Burgan and Rothermel, 1984; Andrews and Bradshaw, 1990) fire behaviour prediction and fuel modelling system was among the early computer systems developed for wildland fire management (Andrews, 2007). Actually, BehavePlus 3.0 (Andrews et al., 2005) is the successor of the BEHAVE, and reflects the updates and expansions and can be downloaded from the Internet (www.fire.org) and run from a personal computer. The output parameters provided by BehavePlus 3.0 are surface head fire rate of spread[2] (m min^{-1}), reaction intensity[3] (W m^{-2}), heat per unit area (kJ kg^{-1}), fireline intensity[4] (kW m^{-1}), and flame length (m). While BEHAVE is very useful for

---

[2] $R = \dfrac{I_r \pi (1+\varphi_w+\varphi_s)}{\rho_b \varepsilon Q_{ig}}$ (Rothermel, 1972)

[3] $I_r = \Gamma' W_n h \eta_m \eta_s$ (Rothermel, 1972)

[4] $I_b = \dfrac{H W_n R}{60}$ (Byram, 1959)

For a more detailed explanation refer to Salis (2008) predicting fire characteristics for a given area, the output is inherently non-spatial. Each calculation is based on the assumption that conditions are uniform and constant for the projection period. In other words, the spread rates, flame lengths, fireline intensities, and heat calculations generated by BEHAVE are applicable only as the specified fuel type, topographic, and weather related parameters do not vary.

In order to develop custom fuel models describing the Mediterranean vegetation, specifically Italian maquis, the row data collected in the field work and grouped in four fuel type, were generalized adapting the methodology developed and explained in BEHAVE-Subsystem FUEL (Burgan and Rothermel, 1984), to be used in BehavePlus 3.0 (Andrews et al., 2005).

The fuel load components required by the model, distinguishing dead and live fuel and, for dead fuel, the 1 hr, 10 hr, 100 hr timelag size classes, are described in Table 24. Even though a fuel model contain several fuel size classes, each having a different surface-area-to-volume ratio (σ), the mathematical fire model requires only the SAV ratio value for 1 hr dead and live components, which is the smallest fuel with the most effect on spread rate. The mean of SAV data, determined considering the most representative species surveyed in the sampling areas and the gathered bibliographical data, were assigned to every sampling plots. As suggested by Burgan and Rothermel (1984), the depth of the fuel layer was set as the 70 percent of the maximum depth. 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.

BehavePlus 3.0 was run to evaluate the desiderated range of potential fire behavior using as input data the fuel values of each custom fuel model. In this study, several burning conditions were set, combining two moisture scenarios and three wind speed. The dry scenario was simulated setting dead 1hr fuel moisture at 8%, dead 10 hr at 11% and dead 100 hr at 13%. The live shrub moisture was set at 60%, whereas the live herbaceous at 30%. The moist scenario was simulated setting dead 1hr fuel moisture at 14%, dead 10 hr and dead 100 hr at 15%. The live shrub moisture and live herbaceous were set at 100%. All fire behavior predictions refer to horizontal terrain.

Table 24. Fuel components needed by BehavePlus 3.0 by size class

Particle diameter (cm)	*Timelag class*	*dead*	*live woody*	*live herbaceous*
< 0.6	1 hr	✓ (shrub + herbaceous + litter + downed woody)	✓ (shrub)	✓
0.6 -2.5	10 hr	✓ (shrub + downed woody)		
2.5 - 7.5	100 hr	✓ (shrub + downed woody)		

7.5. Mapping Fuel Type

An area of 144 square kilometers within the experimental area was mapped by multispectral classification of remotely sensed data. This is the process of sorting pixels into a finite number of individual classes, or categories of data, based on their data values. If a pixel satisfies a certain set of criteria, the pixel is assigned to the class that correspond to those criteria. The technique was applied on one IKONOS high resolution image (June 2006) (Figure 42), using the supervised classification algorithm implemented in ERDAS IMAGINE 9.1 (Leica Geosystems Geospatial Imagine, Norcross, GA, USA). Three basic steps were involved using classifications procedure: 1) training stage, 2) classification stage, and 3) accuracy assessment.

The IKONOS satellite has panchromatic and multispectral sensors with resolution of 0.8 m and 4 m, respectively. The sensor has coverage of 11 km x 11 km, and a high revisit frequency of 3 to 5 days off-nadir and 144 days for true-nadir. From the fusion of these images it is possible to obtain pan-sharpened data with resolution between 0.80 and 1 m. The panchromatic sensor collects information at the visible and near infrared wavelengths and has a band-width of 0.45-0.90 µm. The multispectral sensor acquires data in four spectral bands from blue to near infrared (NIR), as showed in the Table 25. The sensor collects data with 11-bit (0-2047 grey level) sensitivity and is delivered in an unsigned 16-bit (0-65565) data format.

Table 25. IKONOS spectral channels

Band	Band width (µm)	Spatial resolution
1 (Blue)	0.445-0.516 µm	0.80 m
2 (Green)	0.506-0.595 µm	0.80 m
3 (Red)	0.632-0.698 µm	0.80 m
4 (Near IR)	0.757-0.853 µm	0.80 m

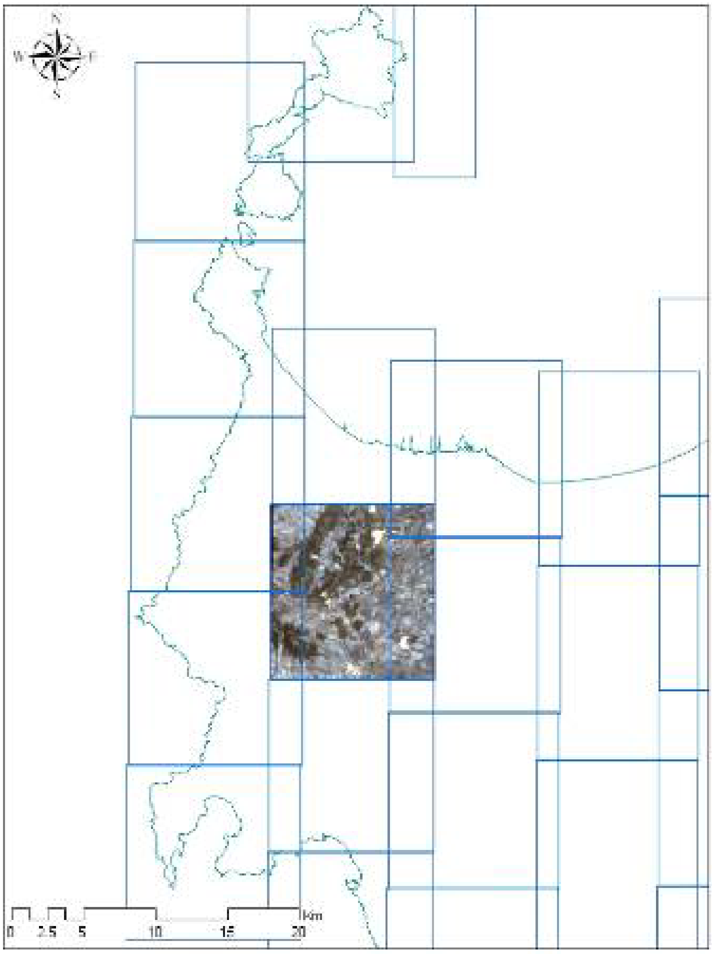


Figure 42. IKONOS high resolution images (06/26/2006)

7.5.1. Training stage

This phase consist in the training (or instruction) of classification algorithm using the spectral characteristics of known and homogeneous areas, constituting the *training fields* or *training sites* (Erdas Field Guide, 2002), indicating the geographical area of interest in the image represented by the pixels in a sample. The identification and localization of the *training sites* was carried on through a combination of fieldwork (to constitute the *ground truth dataset*), aerial photography analysis, available maps and personal experience (e.g. Mausel et al., 1990).

The ground truth dataset was composed by 30 small plots belonging to (1) four sampling study areas falling into the IKONOS, and (2) a set of nondestructive measurements (Appendix 4). An effort was made to ensure that the nondestructive sample was representative of the different potential fuel types. However, the data set was mainly comprised of measurements achieved in a buffer area of 50 m near the local and private roads that crossed the area. The plots were relatively small to match the potentially small grain size of fuel information available from IKONOS (2.5 m x 2.5 m, corresponding to 10 pixels). Measurements at each site included: position data collected by a differential correction GPS (TrimbleNavigation, PathFinder basic plus), dominant species, plant height and cover degree of shrubs.

Other 40 small areas were selected, based on aerial photography and IKONOS analysis and personal experience. The entire dataset of small areas, identified over the IKONOS image, represented significant homogeneous patches corresponding to areas representative for each fuel type class, carefully identified on the basis of the a priori knowledge of the area. Moreover, the maquis fuel type recognized during the field work, classes concerning "agriculture and pasture fields", "woody", and "no fuel" were added.

7.5.2. Classification stage

Each pixel in the image data set was categorized into the fuel type class, which is the most closely resembled. The category label assigned to each pixel in this process was then recorded in the corresponding cell of an interpreted data set. The classification performed in this study was supervised classification, with the algorithm *Maximum likelihood* (ML), which equation is as follow:

$$D = \ln(a_c) - [0.5\ln(|Cov_c|)] - [0.5(X - M_c)T(Cov_c - 1)(X - M_c)] \quad (15)$$

where:

D= weighted distance (likelihood)

c= a particular class

x= the measurement vector of the candidate pixel

M_c= the mean vector of the sample of class c

a_c= percent probability that any candidate pixel is a member of class c

Cov_c= the covariance matrix of the pixels in the sample of class c

| Cov_c |= determinant of Cov_c

Cov_c -1= inverse of Cov_c

ln= natural logarithm function
T= transposition function

This algorithm quantitatively evaluates both the variance and covariance of the category spectral response patterns when classifying an unknown pixel, assuming that the distribution of the cloud of points forming the category training data is Gaussian (normal). Pixels were thus assigned to the class of highest probability. The probability of a pixel belonging to each category was computed, and then assigned to the most likely class or labeled "unknown" if the probability values were below a threshold. Eventually, a multidimensional image matrix is used to develop a corresponding matrix of interpreted land cover category types. After the entire data set was categorized, results were obtained in the output stage.

7.5.3. Evaluating the Classification

The assessment of the classification accuracy was performed by the comparison of classified data and geographic data assumed to be true (*reference pixels*). One pixel per ground truth plot was selected for the classification accuracy assessment (whereas the surrounding area with the same fuel type was used for the training), and other reference pixels were randomly extracted on the output classification by the software. Therefore, no training pixels were used for the classification accuracy assessment.

An error matrix between actual and simulated data was calculated to define the frequency of each fuel model class. The accuracy of the classification was evaluated using the following statistical indicators derived from the error matrix: overall accuracy, user's accuracy, producer's accuracy, and Cohen's kappa coefficient (Congalton and Green, 1999; Congalton, 1991). The o*verall accuracy* is computed by dividing the total number of correctly classified pixels by the total number of reference pixels. The *producer's accuracy* is computed by dividing the number of correctly classified pixels in each category (on the major diagonal) by the number of training set pixels used for that category (the column total). This figure indicates how well training set pixels of the given class are classified. The *user's accuracy* is computed by dividing the number of correctly classified pixels in each category by either the total number of pixel that were classified in that category (the row total). This figure is a measure of the commission error and indicates the probability that a pixel classified into a given class actually represent that category on the ground.

Cohen's kappa coefficient (k) is a standard nonparametric measure of the classification accuracy, which allows for the evaluation of the overall agreement between simulated and actual classes after random agreements by chance are removed. k values were calculated as follows:

$$k = \frac{observed\_accuracy - chance\_agreement}{1 - chance\_agreement} \tag{16}$$

$$k = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}\left(x_{i+} \cdot x_{+i}\right)}{N^2 - \sum_{i=1}^{r}\left(x_{i+} \cdot x_{+i}\right)} \tag{17}$$

where

r= number of rows in the error matrix
x_{ii}= the number of observations in row I and column I (on the major diagonal)
x_{i+}= total of observation in row I (shown as marginal total to eight of the matrix)
x_{+i}= total of observations in column I (shown as marginal total at bottom of the matrix)
N= total number of observations included in matrix

7.6. FARSITE simulations and sensitivity

The last part of the work regarded the evaluation of the capabilities of fuel model themes and fuel map in simulating the fire spread and behaviour by spatially and temporal explicit fire simulators, such as FARSITE, with the aim of better understand if different fine scale fuel maps, at 5, 10 and 15 m, would affect the fire spread and behaviour. The percent difference between outputs was calculated

$$\%\_difference = \frac{(y_o - y_1)}{y_0} \qquad (18)$$

where y_0 was the reference parameter and y_1 was the output parameter when the value of the input parameter was changed.

The area study was random localized inside the IKONOS satellite image previously classified (Figure 43).

Figure 43. Area study for FARSITE simulations

FARSITE simulations required a set of spatial information of the three main environmental factors that affect the fire behaviour (Figure 44): topography, vegetation and meteorological conditions. All this input layers required were provided in ASCII format, and managed by using ArcGIS (ArcGis 9, ESRI Inc., Redlands, CA, USA).

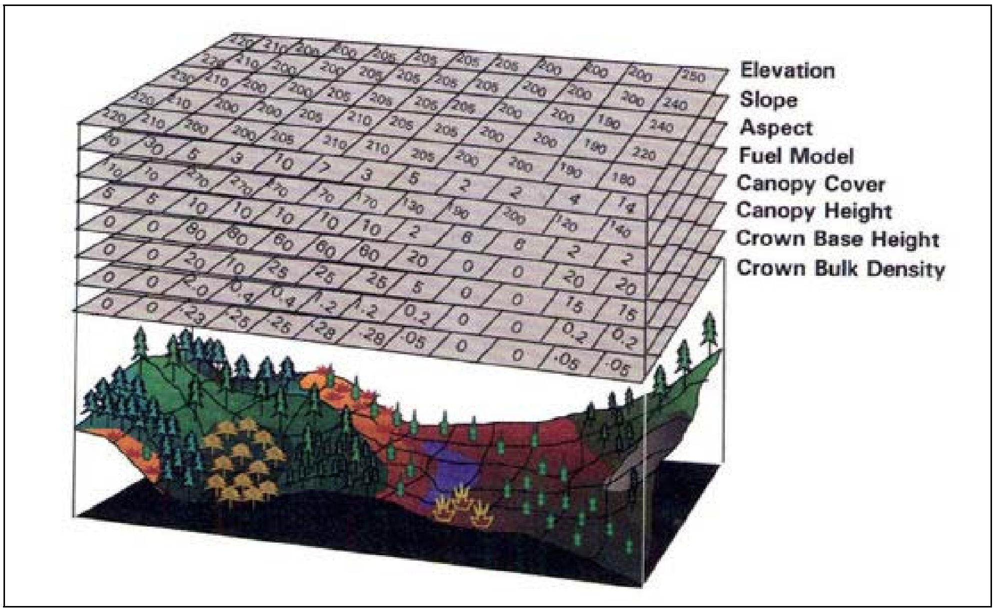


Figure 44. FARSITE input layers for landscape topography and vegetation (from Finney, 2007)

The *topography factor* was composed by three different layers: elevation, slope and aspect. 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.

The *vegetation layer* was composed by fuel model maps. The fuel model map gives a detailed physics description of the landscape surface vegetation, by using appropriate standard or custom fuel models. Several fuel model layers were created from the best fuel type classification, assigning custom fuel models previously developed and standard fuel model to the fuel type as follows: CM1 to open and low maquis, CM2 to medium maquis, CM3 to medium height and close maquis, CM4 to high and close maquis, FM1 (Anderson, 1982) to agriculture and pasture, FM99 (Scott and Burgan, 2005) to the areas classified as no fuel and woody.

The fuel model map gave a fuel model code for each point of the grid. For each fuel model code the values of the same physical characteristics used in BEHAVE must be provided by an ASCII file.

For the fuel moisture information the dry scenario condition (see § 7.4.2) were used, set constant for every custom fuel model. 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.

These five indispensable layers constituted in FARSITE the "Landscape File (.lcp)", which contained all the landscape spatial information. The resampling of the five layers through the Nearest Neighbour classifier algorithm (Figure 45) (Spatial Analyst tool, ArcGIS 9.) allow to obtain three landscape file, with different fine resolution of 5, 10, 15 m. All the raster themes were converted into raster ASCII format, in order to support the definition of the landscape file into FARSITE simulator.

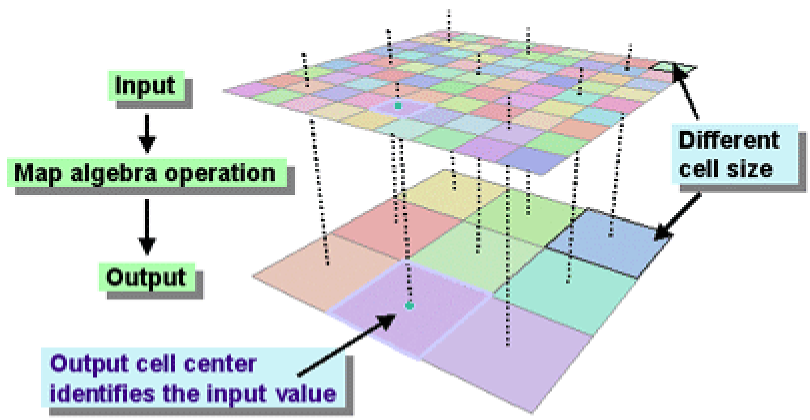


Figure 45. Resampling method to a coarser resolution
(from *http://webhelp.esri.com/arcgisdesktop/9.2*)

The fire simulation was dependent upon local weather conditions such as moisture and wind direction. The *meteorological conditions* of the wildfire days were considered by a weather file (.WTR). This file contains daily observations on temperature, hours at which minimum and maximum temperature were recorded (19 and 20°C respectively), minimum and maximum humidity (33% and 81%) and precipitation (0.0 mm). The *wind data* inserted in FARSITE was required at 6.1 m above the top of vegetation. The wind file (.WND) was composed by three hourly data: wind speed (5 and 10 km h^{-1}), wind direction (NW) and cloud cover (0%).

For all simulations, the adjustment factor for fire rate of spread was set at 1.0 for all fuel models. Raster outputs produced by FARSITE for the fire behaviour characteristics have ASCII format, thus all the simulation outputs have been exported and managed by using a GIS. For each simulation the fire perimeter and rate of spread raster outputs have been exported, in order to understand and to describe fire behaviour.

8. RESULTS AND DISCUSSION

In this chapter the experimental results obtained during this study are showed. They can be summarized in:

1. Characterization of the study areas based on the fuel complex properties (height and cover) and fuel components load (live and dead subdivided into the diametric classes).
2. Analysis of the relationships between fuel complex properties and fuel load.
3. Maquis fuel type characterization
4. Fire behaviour custom fuel model development with Behave 3.0.
5. Remote sensing data elaboration and classification.
6. Sensitivity analysis of FARSITE simulations using three resolution fuel maps

8.1. Characterization of the study areas

This section summarizes the results obtained from the analysis of both plant height and plant cover data collected along transects. Table 26 showed the species detected in all the eight areas. *Pistacia lentiscus, Cistus monspeliensis, Calicotome spinosa* and *Chamaerops humilis* were the dominant shrub species that can be observed in almost all the experimental sites, while *Arbutus unedo* and *Phillyrea angustifolia* were only observed in restricted areas characterized by different soil types or vegetation evolution.

Table 26. Species detected during the field survey

Species	Specie codes	LC1	LC2	LC3	PP	RU	MD1	MD2	MF
Arbutus unedo L.	ARBUNE	x			x				x
Calicotome spinosa (L.) Link	CALSPI		x	x	x	x		x	x
Chamaerops humilis L.	CHAMHUM		x		x	x	x	x	
Cistus monspeliensis L.	CISMON	x	x		x	x	x	x	x
Cistus salvifolius L.	CISSAL				x	x			x
Daphne gnidium L.	DAP		x		x		x	x	
Dorycnium pentaphyllum L.	DORYC						x		
Erica arborea L.	ERICA					x			x
Lonicera implexa L.	LONIMP	x	x		x				x
Myrtus communis L.	MIRCOM	x	x	x		x			x
Olea oleaster Hoffmg. et Link	OLOLEAS				x				
Phillyrea angustifolia L.	FIL	x			x				
Pistacia lentiscus L.	PISLEN	x	x	x	x	x	x	x	
Pyrus pyraster Burgsd.	PIRPIRAS	x							
Quercus ilex L.	QUIL		x		x				
Rhamnus alaternus L.	RAMN	x							
Rosmarinus officinalis L.	ROSMOFF				x		x		

Shrubland (or Mediterranean maquis) represents the dominant vegetation (Figure 46). Only the areas MD1 and LC2, burned respectively during the 2006 and 2005 summer seasons, showed a shrub cover smaller than 63%. In area MD1, the 36.8% was characterized by bare soil, while in the area LC2 just the 6.3% was bare soil and the contribution of the herbaceous component to the ground cover reaching the 28% of the total; the herbaceous components in area LC3, where fire occurred in 2004, contributes with the 5.6%; finally, in the unburned areas the contribution of the herbaceous species was minimal, not exceeding 1%.

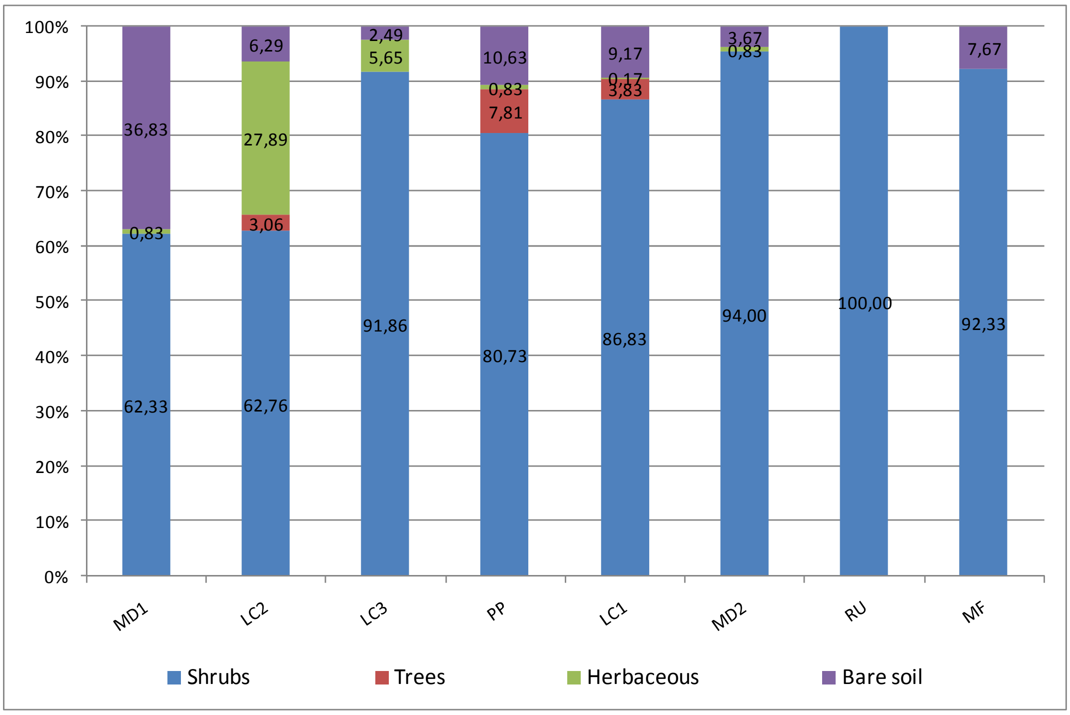


Figure 46. Cover degree surveyed along the transect

Figure 47 presents the specific plant cover surveyed in the areas MD1, LC2, LC3, and PP, burned respectively during the 2006, 2005, 2004, and 1999. In area MD1, where the fire occurred in the 2007, the dominant species were *Cistus monspeliensis* and *Chamaerops humilis* (both covering the 20%). In area LC2, *C. monspeliensis* and *C. humilis* did not reach 10% cover, whereas *Calycotome spinosa* contributed to 12% of cover. In area LC3, burned in 2004, the dominant species were *Myrtus communis* (35%), *C. humilis* (30%) and *Pistacia lentiscus* (28%). Finally in area PP, at eight years post-fire, the species that mainly contribute to the cover were *Cistus salvifolius* and *C. spinosa*, respectively at 34%

and 22%. Except for area LC3, the other recently burned areas are dominated by seeder species, as *C. monspeliensis*, *C. salvifolius, C. spinosa,* and *R. officinalis*.

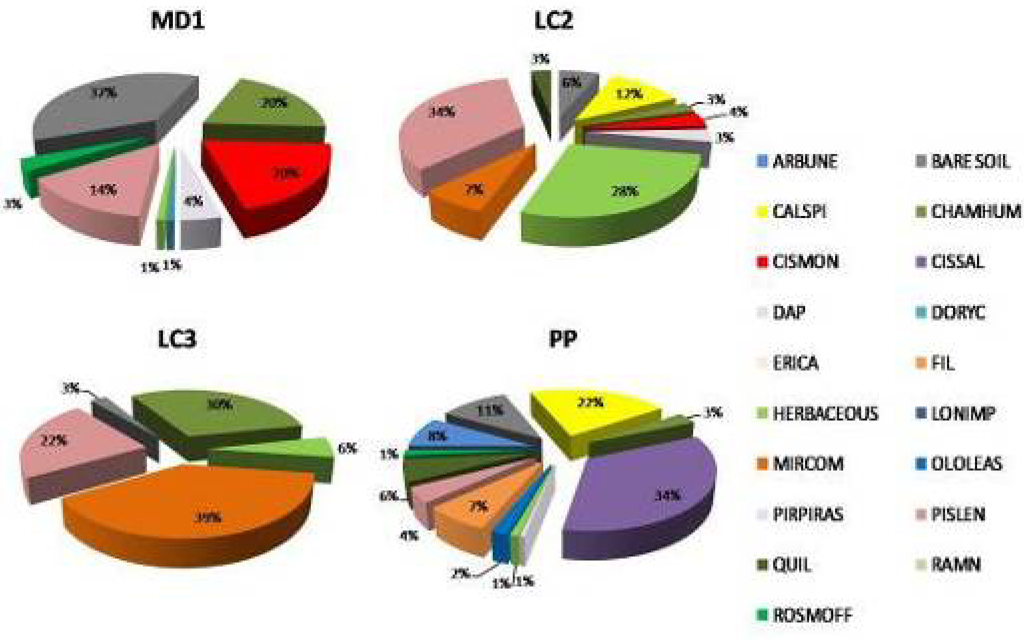


Figure 47 Species cover surveyed in the burned areas

In Figure 48 the cover in the areas not burned in the last 15 years (LC1, RU, MD2, and MF) is showed. Generally, the species that mainly contribute to the cover were *M. communis*, present in three out of four areas with a range varying from 9% in the area MF to 65% in the area 5, and *P. lentiscus*, present in three out on four areas (MD2, RU, and LC1, respectively 6, 27, and 28%). Area MF appeared distinctive in composition, since *Arbutus unedo* represented by its own the 57% of the cover, followed by *Erica arborea*, 17%. *C. spinosa* and *C. monspeliensis* were both present in area MD2 (16 and 35% respectively), indicating that this area was probably the more degraded among the unburned areas.

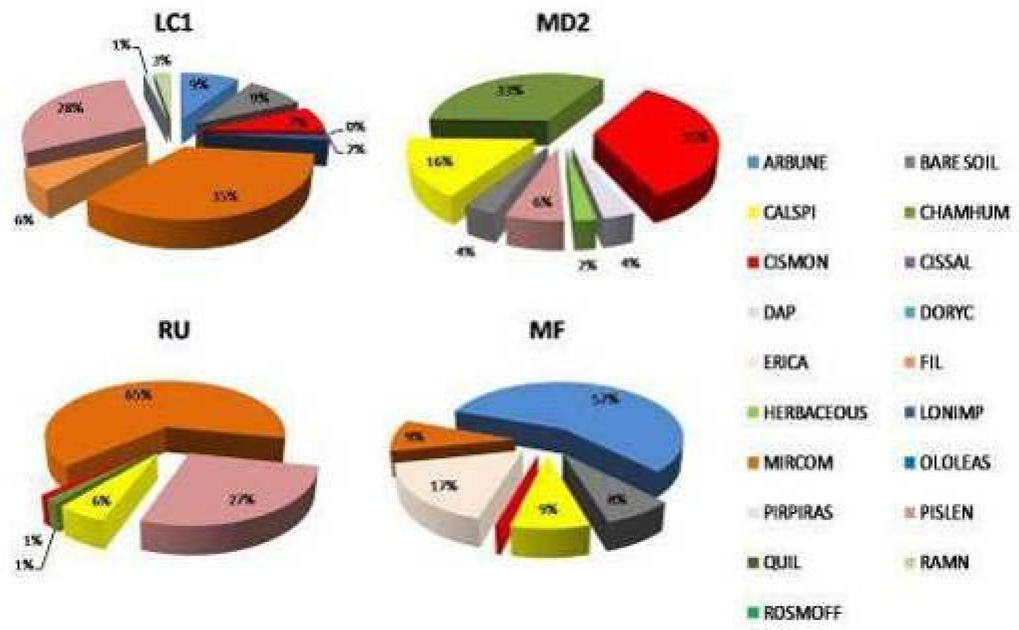


Figure 48 Species cover in unburned areas

The data collected along the transects were used as inputs in the statistical software STADIV (Ganis, 1997) with the aim to evaluate several ecological index of richness and diversity between the burned and unburned areas, and within the areas. In Table 27, species richness (or species abundance), that is the total number of species present in the area, was computed through the Margalef index (Margalef, 1960), which is an attempt to estimate species richness independently of the sample size. The values provided by the Margalef index confirmed the data obtained along the transects, indicating PP as the richest area between burned and unburned sites and within the burned areas. On average, the burned sites showed higher richness respect to the unburned areas.

Table 27. Margalef index for species richness

Areas	*Margalef Index*	Areas	*Margalef Index*
MD1	1.011	LC1	1.270
LC2	1.109	MD2	0.786
LC3	0.471	RU	0.625
PP	1.590	MF	0.633

Moreover, in every area the floristic diversity relative to the surveyed shrub species, responsible for the vegetation structure, was quantified with Shannon index (Shannon, 1948). The effective number of species contributing to the diversity, that is the number of species of equal abundance giving the Shannon index value (H), was computed through Hill's number (1973). Once again PP was the area with higher floristic diversity regarding the shrub vegetation, followed by area LC2, burned in the 2005. The areas RU and MF, unburned, were distinguished by a low Shannon index and Hill's number: in these areas, the number of specie that contribute to the diversity was 2.5 and 2.9.

Table 28. Shannon Index and Hill's Number in the eight study areas

Areas	*Shannon Index*	*Hill's Number*
MD1	1.513	4.54
LC2	1.649	5.203
LC3	1.231	3.426
PP	1.795	6.022
LC1	1.569	4.802
MD2	1.424	4.154
RU	0.898	2.454
MF	1.083	2.954

Regarding the plant height, the areas showed differences, mainly between burned and unburned areas. The average height of the shrub vegetation ranged from 0.5 to 2.3 m in the eight test areas. Figure 49 showed the mean height and 95% confidence interval for mean; Table 29 evidenced the mean, maximum and minimum heights in the burned and unburned areas: in burned areas the vegetation did not exceed the meter of height, while the unburned areas were characterized by a greater variability with a range that goes from 1.08 in area LC1 to 2.33 m in MF. Moreover, one way ANOVA and LSD test *post hoc* were performed to evaluate the differences between height across the burned and unburned sites, revealing significant difference at $p < 0.05$, as shown in Figure 49.

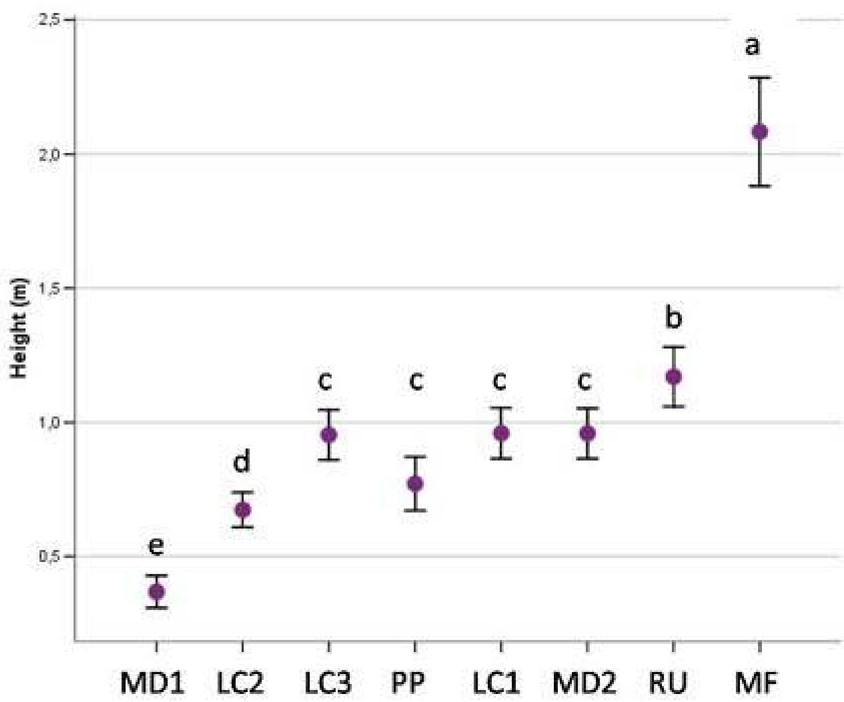


Figure 49. Mean height measured along the transect and 95% confidence interval for mean. The areas marked with different letter are significantly different at p< 0.05 with LSD test

Table 29 Mean, maximum and minimum height (m) in the burned and unburned areas

	Burned				Unburned			
	MD1	LC2	LC3	PP	MD2	LC1	RU	MF
mean	0.36	0.67	0.95	0.77	0.95	0.96	1.17	2.08
min	0.10	0.15	0.20	0.15	0.20	0.20	0.25	0.20
max	0.85	1.18	1.50	1.50	1.58	2.19	1.97	3.50

The average height of the shrub vegetation was also collected into the plots. Figure 50 showed the mean and 95% confidence interval for mean: the unburned areas were characterized by a greater variability, as already pointed out in the transect data. Statistical differences were evidenced (LSD, p< 0.05) in Figure 50 between recently burned areas (LC2, LC3, PP, and MD1) and unburned areas (LC1, RU, MD2, and MF): the areas significantly different were marked with different letter.

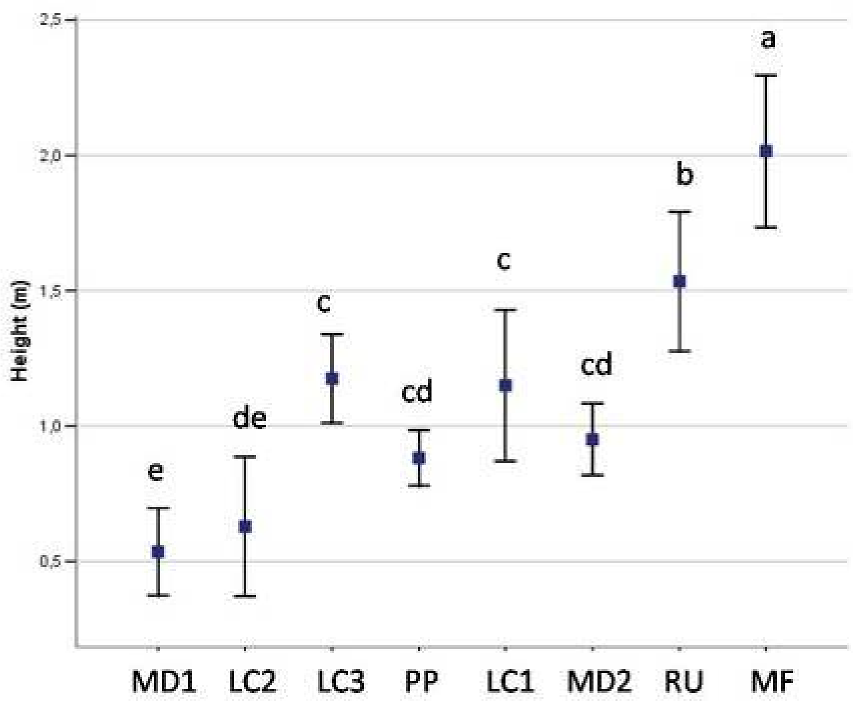


Figure 50. Mean height measured into the plots and 95% confidence interval for mean. The areas marked with different letter are significantly different at $p< 0.05$ with LSD test

After the analysis of the digital photos with AutoCad 2002, the cover of surveyed species in the areas MD1, LC2, LC3 and PP was estimated, as shown in Figure 51. The data show that bare soil represent 16% in the recently burned areas, whereas in the other areas it varied between 4% and 14%. The herbaceous component contributed 19% to cover in area MD1, and decreased to 10% in area LC3. The dominant species in area MD1 were *Cistus monspeliensis* and *Chamaerops humilis* (19 and 13%). In the area burned two years before this study, *C. monspeliensis* reached 33%, *C. humilis* did not reach 5% of cover, while *Calycotome spinosa* was not surveyed in the plots. The dominant species in area where fire ran through in 2004 were *P. lentiscus* (32%), *C. humilis* (28%) and *M. communis* (26%). Finally, in the area PP, burned during 1999, the species that mainly contributed to the cover were *C. monspeliensis, A. unedo* and *P. lentiscus*.

In the unburned areas, among the species that mainly contribute to the cover, *M. communis* was in three out of four areas ranging from 19% in area MF till 45% in area RU (Figure 52); also *P. lentiscus* was surveyed in three areas (area MD2, RU, and LC1 respectively 9, 55, and 41%). *Arbutus unedo* was in area MF as 40% of cover, followed by *M. communis* and *Erica arborea* (19 and 17%). *C. spinosa*, contributing 9% to cover with the transect methodology, in this case concurred with 5%, whereas *C. monspeliensis* contributed from 35% to 14% in area MD2.

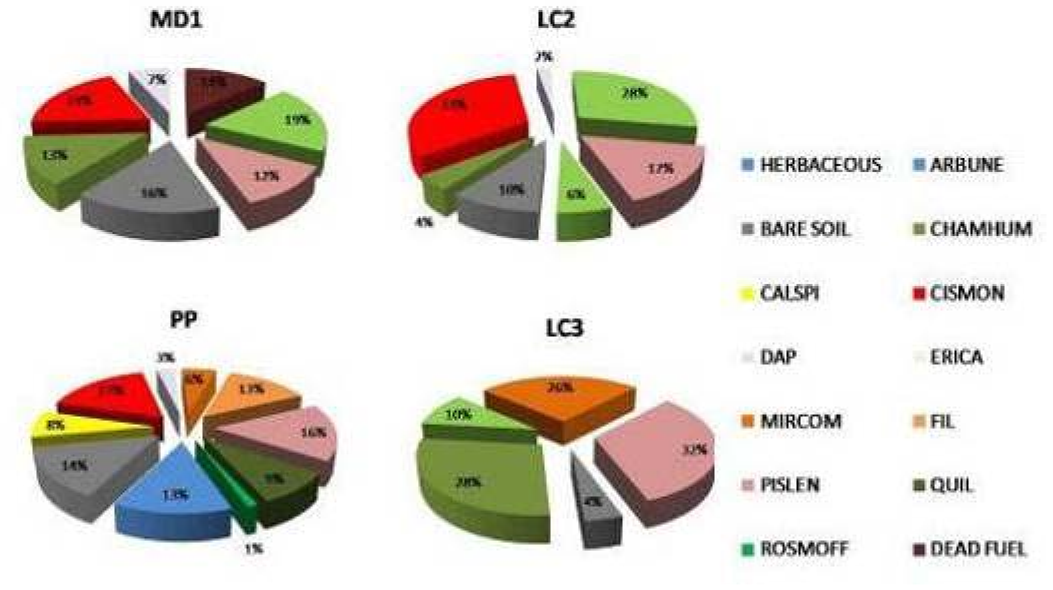


Figure 51. Species cover surveyed in the burned areas with the digital photos images

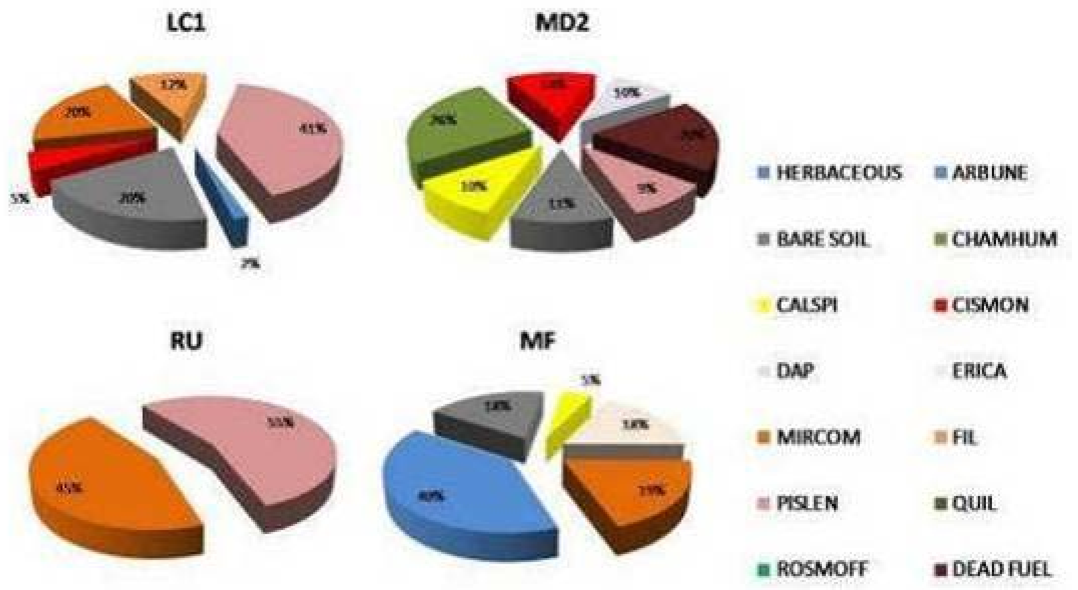


Figure 52. Species cover surveyed in the burned areas with the digital photos images

8.2. Fuel load

8.2.1. Amount and distribution of fuel load

Other conditions being equal, the amount of heat produced by a burning fuel bed is strongly influenced by the amount of fuel available to burn. In this study, the fuelbed characteristics of both burned and unburned sites were compared. A preliminary examination of the live, dead and total shrub load data partitioned in burned and unburned areas, revealed not serious threats to the assumption of normality or homogeneity of variance respectively for total shrub load (Figure 53) and shrub live load (Figure 54).

The dead material was tested through the Mann-Whitney non parametric test, because it was not normally distributed; results provided by this test did not show any significant differences between burned and unburned areas

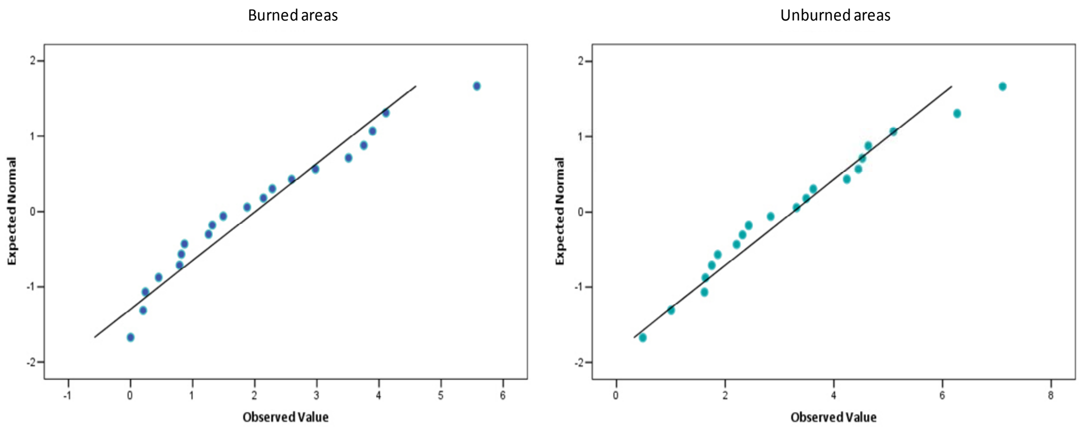


Figure 53. Total shrub fuel load Q-Q plots across burned and unburned sites

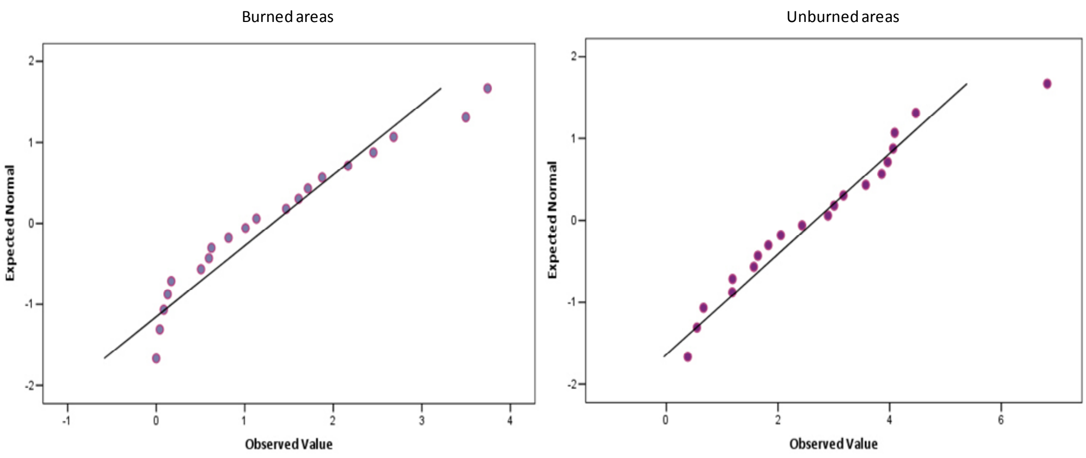


Figure 54. Live shrub fuel load Q-Q plots across burned and unburned sites

Moreover, one way ANOVA and LSD test *post hoc* were performed to evaluate the differences of live fuel load within burned sites and unburned sites, revealing that the recently burned areas (MD1 and LC2) showed significant differences from the others, as well as the unburned area RU. In Figure 55, the areas marked with different letter are significantly different (LSD test, $p< 0.05$).

The burned areas are characterized by an average total fuel load of 20.07 Mg ha^{-1}, varying between 10.37 Mg ha^{-1} in area MD1, burned during the late spring 2006, and a maximum of 32.07 Mg ha^{-1} in area LC3, burned in 2004. The unburned areas were distinguished by an average of 32.45 Mg ha^{-1}, varying from 24.06 Mg ha^{-1} in area MD2 to a maximum of 46.32 Mg ha^{-1} in area RU.

The average load of live material in the unburned areas was 26.69 Mg ha^{-1}, with a wide range of variation (17.85 Mg ha^{-1} in area MD2 to a maximum of 41.48 Mg ha^{-1} registered in RU); in burned areas, the fuel loads were broad from a minimum of 5.17 Mg ha^{-1} in MD1 to a maximum of 20.55 Mg ha^{-1} in PP, with an average of 13.15 Mg ha^{-1} (Table 30).

As referred by several studies (Countryman, 1982; Saglam et al., 2008), living fuels is the major constituent of the standing fuel in shrub; data presented in study relative to unburned plots and in plots burned in 1999 confirmed this statement.

As other Mediterranean ecosystems, in the maquis the dead fuel material is intermixed with the living fuel, influencing the amount of thermal energy released, and allowing the ignition of the fine living fuels. In this study not significant differences were observed between burned and unburned areas, respectively equal to 5.77 Mg ha^{-1} and 6.92 Mg ha^{-1}. Tabulation of the total fuel load split up in percent live and dead material (Table 30) showed that the average proportion of biomass in the burned sites was 62%, whereas in the unburned areas was 81%; the average percentages of dead material were 38 and 19%, respectively. As it is possible to see from Table 30, PP site, even if burned in 1999, followed the trend reflected by the unburned sites. It is interesting to notice that the ratio *necromass/biomass* in the unburned areas was always smaller than 0.4, that is, the shrub necromass did not reach the 2/5 of the biomass. Contrary, in the area burned recently, this ratio was usually more than 0.5, except for PP. In areas LC2 and MD1, characterized by recent fires, the necromass percent was comparable to the biomass, with a ratio *necromass/biomass* equal to 1 or less superior.

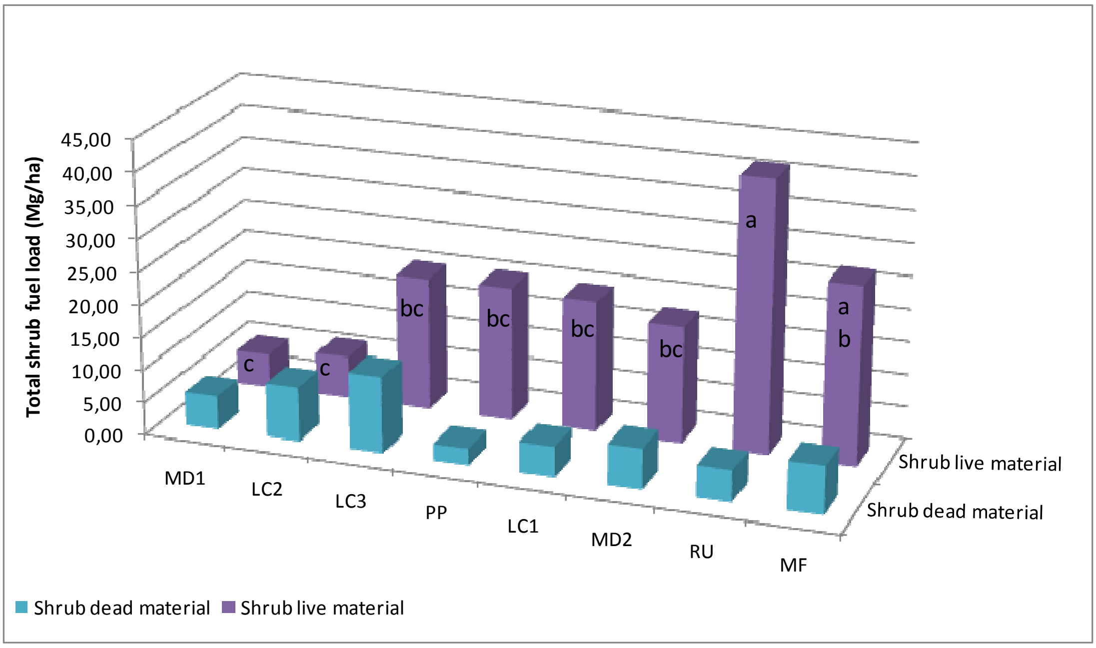


Figure 55. Distribution of the collected vegetative material between live and dead. The areas marked with different letter are significantly different at p<0.05.

Table 30. Percent distribution of the collected total shrub fuel load between live and dead

	Total shrub fuel load (Mg ha^{-1})	
	Live	Dead
MD1	5.18 *(49.9%)*	5.20 *(50.1%)*
LC2	6.47 *(43.8%)*	8.29 *(56.2%)*
LC3	20.41 *(63.6%)*	11.66 *(36.4%)*
PP	20.55 *(89.1%)*	2.52 *(10.9%)*
LC1	20.10 *(81.2%)*	4.65 *(18.8%)*
MD2	17.85 *(74.2%)*	6.20 *(25.8%)*
RU	41.48 *(89.6%)*	4.84 *(20.4%)*
MF	27.32 *(78.7%)*	7.37 *(21.3%)*

8.2.2. Size class partitioning

Shrub fuels contain particles with various sizes, ranging from foliage and small twigs to large main stems and trunks. Because of their greater surface to volume ratio, small fuels ignite more easily and burn more rapidly that do large fuels (Countryman, 1982). Moreover, it is well known that one of the major determinants of the amount of fuel that will burn is the relative quantity of fuels of different sizes in the fuel bed. The dead fuel load consists of the following four components, classified according to the time fuel takes to reach the equilibrium with humidity variations in atmosphere: 1 hr (0-0.6 cm), 10 hr (0.6-2.5 cm), 100 hr (2.5-7.5 cm), and 1000 hr (>7.5 cm). The same convention is currently applied on live materials.

One way ANOVA and LSD test *post hoc* were performed to evaluate the differences within burned and unburned sites, revealing significant differences (at $p < 0.05$). In Figure 56, the areas marked with different letter were significantly different (in capital for unburned areas). Quantitative differences could be observed between recently burned areas (MD1, LC2, LC3, PP) and unburned areas, in which the passage of the fire happened more than 15 years from the dates of sampling (LC1, RU, MD2, MF). Diameters higher than 7.5 cm (L 1000 hr) were only in two areas, LC3 and MD2, while the other dimensional classes were widely represented in all the study areas (Figure 56). In general terms, considering only the component L 1, the burned areas were characterized by a wide load range (from 3.54 to 12.52 Mg ha^{-1}), and this component increased with the time after the passage of the fire, as well as L 10 component (from 0.4 to 7.72 Mg ha^{-1}). In area LC2 and PP, the fractions of live material were reduced with the increasing of the diameters, but such trend was not respected in the others two unburned areas. Considering the percentage composition of the four dimensional classes on the total live material (Table 31), burned areas had a finer dimensional component (< 0.6 cm) in proportion more abundant (from 58.5 to 69.6%) compared to unburned areas (from 35.7 to 44.0%); differently, L 10 turned out to have a greater weight in the unburned areas. Exception must be made for MD2, in which the percentage of L 10 was modest, exceeded by L 1000.

The fine live component, consisting in green leaves and fine woody, showed a general trend: in all sites the percentage of this fraction on the total shrub load was about 35%. This data are similar to the data found by De Luis (2004), where the percentage of green fraction in the total biomass was about 30%, in sites dominated by *Ulex parviflorus*, and the data of Rego et al., (1994), where a typical shrub had 15% leaves and 25% fine woody fuels. Different data are presented by Baeza et al. (2002), in which the live fraction of *U. parviflorus* represented the 51% on total fuel load in recently burned individuals, and 13% in mature individuals.

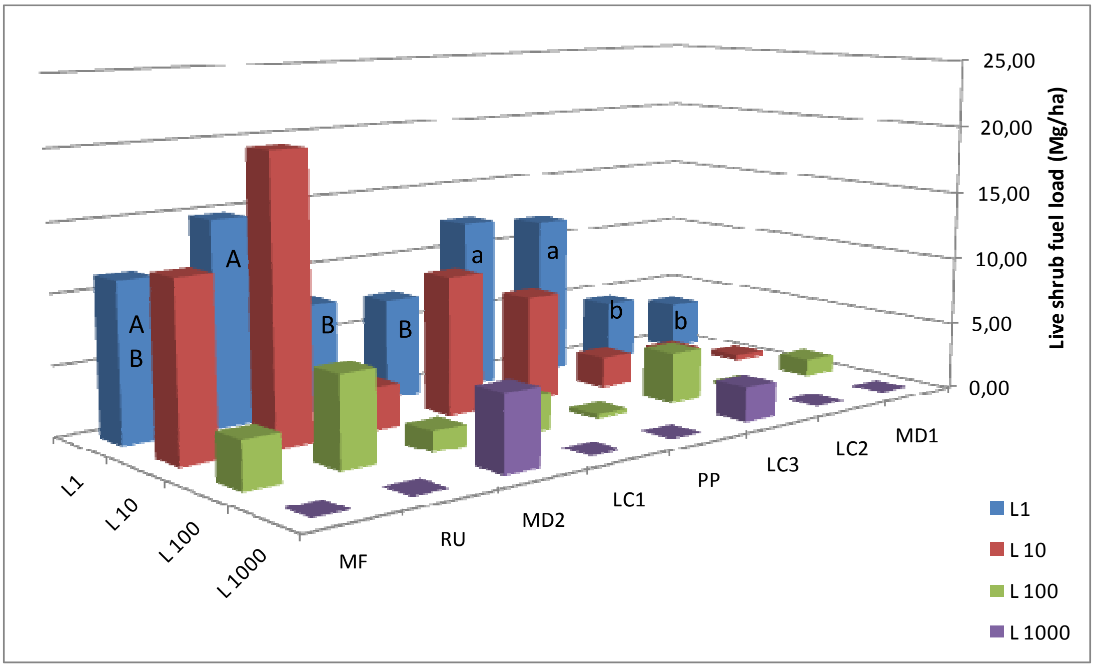


Figure 56. Live shrub fuel load partitioning in the study areas. The areas marked with different letter are significantly different (in capital for the unburned areas) at p<0.05

Table 31. Live shrub fuel load in Mg ha^{-1} and percentage partitioning in the study areas on live shrub fuel load

	Live shrub fuel load (Mg ha^{-1})			
	L 1	L 10	L 100	L 1000
MD1	3.54	0.40	1.24	-
	(68.31%)	*(7.73%)*	*(23.96%)*	-
LC2	4.51	1.73	0.24	-
	(69.62%)	*(26.74%)*	*(3.64%)*	-
LC3	11.95	2.20	3.72	2.55
	(58.53%)	*(10.77%)*	*(18.22%)*	*(12.48%)*
PP	12.52	7.73	0.30	-
	(60.94%)	*(37.61%)*	*(1.45%)*	-
LC1	7.35	10.13	2.61	-
	(36.58%)	*(50.43%)*	*(12.98%)*	-
MD2	7.85	3.08	1.49	5.43
	(43.98%)	*(17.28%)*	*(8.33%)*	*(30.41%)*
RU	14.83	20.21	6.44	-
	(35.75%)	*(48.72%)*	*(15.54%)*	-
MF	11.40	12.56	3.35	-
	(41.73%)	*(45.99%)*	*(12.28%)*	-

The dead shrub fuel load consisted of three components, referred as D 1, D 10, D 100. Considering the areas burned recently (MD1, LC2, respectively in 2006 and 2005), the finest dead component was smaller than in PP, area burned in the 1999, ranging from 1.07 to 1.39 Mg ha^{-1}. In these areas, but also in area LC3 (last fire in 2004), the member D 10 hr resulted to be important (Figure 57).

The proportion of the three dead material dimensional classes on total fuel load tended to fall in the smaller size classes (<2.5 cm) rather than the larger one (Table 32), as referred also by Pereira (1995). Only the dead material at 10 hr showed a different average percent in the burned and unburned areas. In particular, the finest class (<0.6 cm of diameter) of burned areas showed a percent average of 10.8 on the dead material, whereas the coarsest class showed a percent average of 3.8. In general, the fine dead shrub material showed an overall mean value of the 11% on the total fuel load. This data was similar to the data found by Saglam et al. (2008), where the mean value was 13%.

The amount of dead fuel in shrublands can be expected to vary with the age, expressed as years since last fire, but also with the environmental stresses to which it has been subjected, as the drought, or grazing. The little percentage of small dead material on total dead in burned areas (except for PP area) could be attributed not only to seasonal causes, but also to the recent fire occurrence. The dead fine material is important for the ignition and for the consequent fire spread, as well as its intensity. Therefore, it is clear that there was a small fraction into the areas recently burned. Dead fine fuel has been found to accumulate with age in several studies (Rothermel and Philpot, 1973; Papiò and Trabaud, 1991; Fernandes and Rego, 1996), but in this study no clear trend was noticed.

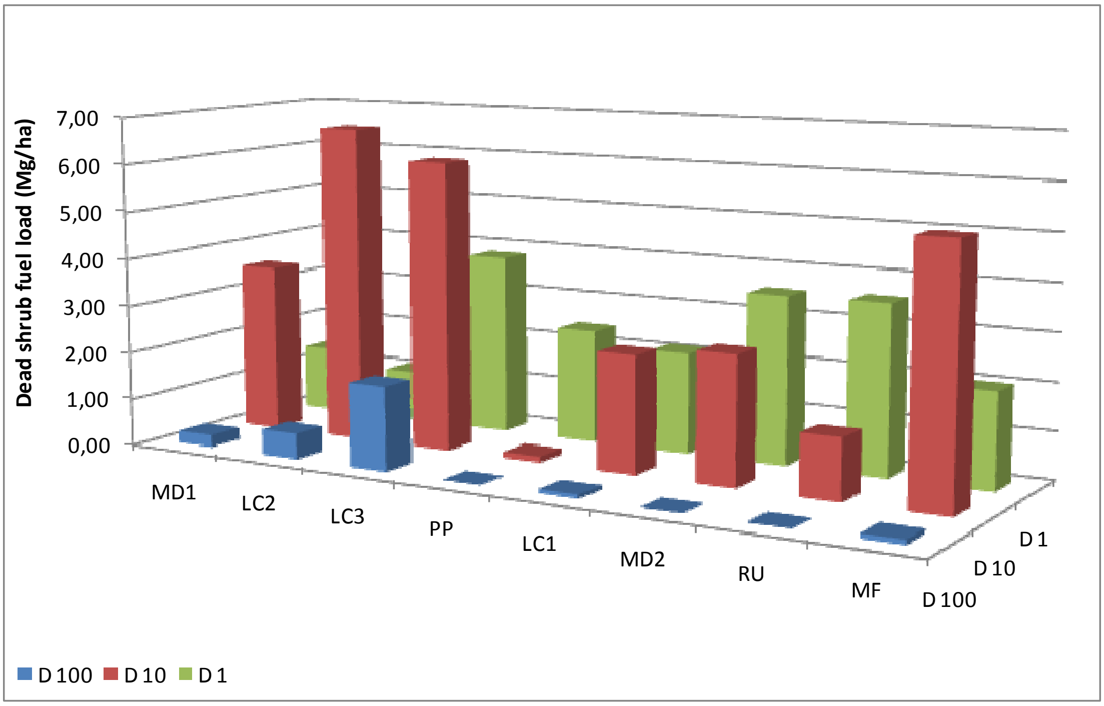


Figure 57 Dead shrub fuel load partitioning in the study areas

Table 32. Dead shrub fuel load in Mg ha^{-1} and diametric classes percentage partitioning on dead shrub fuel load (in brackets and italics) (left part of the table); diametric classes percentage partitioning on total shrub fuel load (right part of the table)

	Dead shrub fuel load (Mg ha^{-1})			% on total shrub fuel load		
	D 1	D 10	D 100	D 1	D 10	D 100
MD1	1.39 *(26.79%)*	3.55 *(68.38%)*	0.25 *(4.83%)*	13.4	34.3	2.4
LC2	1.07 *(12.96%)*	6.69 *(80.66%)*	0.53 *(6.39%)*	7.3	45.3	3.5
LC3	3.82 *(32.76%)*	6.08 *(52.16%)*	1.76 *(15.07%)*	11.9	19	5.5
PP	2.40 *(95.25%)*	0.12 *(4.75%)*		10.4	0.5	
Average %	***41.9***	***51.5***	***8.8***	***10.8***	***24.8***	***3.8***
LC1	2.12 *(45.61%)*	2.45 *(52.67%)*	0.08 *(1.72%)*	8.6	9.9	0.3
MD2	3.53 *(56.86%)*	2.68 *(43.14%)*		14.7	11.1	
RU	3.56 *(73.63%)*	1.27 *(26.37%)*		7.7	2.8	
MF	2.01 *(27.29%)*	5.27 *(71.40%)*	0.10 *(1.32%)*	5.8	15.2	0.3
Average %	***50.8***	***48.4***	***1.5***	***9.2***	***9.7***	***0.3***

The other dead fuel components collected in the plot were the litter (freshly fallen leaves, spines and twigs, less than 0.6 cm of diameter area), dead herbaceous and downed woody material, partitioned by size classes (DW 1, DW 10, and DW 100) (Figure 59). In burned areas, the litter component ranged from 1.32 to 8.96 Mg ha^{-1}, increasing from areas burned two years before the data collection to area burned during the 1999. In unburned areas the litter ranged from a minimum of 8.55 to a maximum of 13.71 Mg ha^{-1}. The litter percentage was low (17.8, 19.3 and 29.8%) in burned areas, exceeding 50% on the total dead fuel load content in eight years old burned area PP, and in unburned areas. In terms of percent on the amount of total fuel collected in the burned areas litter varied from 9.96 to 25.96, whereas in the unburned areas the percent average was 23.67.

A preliminary examination of the litter load data partitioned in burned and unburned areas, revealed threats to the assumption of normality, whereas the Levene test did not show any violation to the homogeneity of variance (Figure 58).

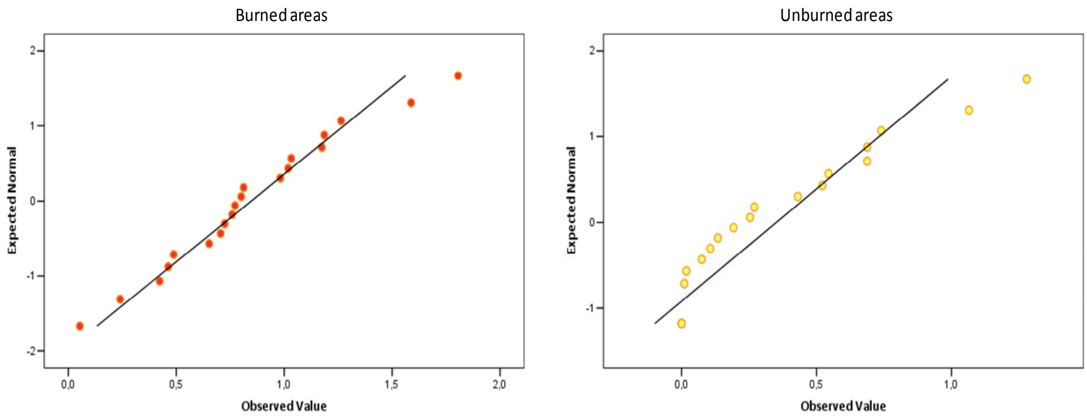


Figure 58. Litter load Q-Q plots across burned and unburned sites

Therefore a Mann-Whitney test was performed, indicating that the litter load medians differed significantly between burned and unburned areas ($p<0.01$). The same *U* test was performed *post hoc* to evaluate all the pairwise comparison, revealing significant differences (at $p< 0.05$) only within burned areas. In Figure 59 the areas marked with different letter are significantly different. MD1 and LC2, burned two years before this study, difference significantly from PP, in which the fire occurred in 1999.

The burned sites were characterized thus by different litter load amount, probably in response to fire, which destroys leaf litter (e.g. Diadema et al., 2007). This effect is particularly important in the Mediterranean ecosystems, where litter decomposition may be very slow due to the coriaceous leaf structure of many species, their high concentration in secondary compounds, and the low moisture content of soils (Arianoutsou and Radea, 2000). However, such differences were found attenuated at least eight years after fire.

Litter layer was an important component of the fuel bed, as showed in Table 33. The data surveyed were different from those collected in other Mediterranean shrub vegetation. In Greece, Dimitrakopoulos (2002) found that the average litter load in evergreen-sclerophyllous shrubland (maquis) up to 1.5 m was 2.51 Mg ha^{-1} , and little higher (3.38 Mg ha^{-1}) in the same vegetation up to 3 m. In California, Countryman (1982) collected dry weight of litter ranging from 6.77 to 49.60 Mg ha^{-1}. These extreme diversities were due probably to the methodologies with which the litter load was collected: according to Countryman (1982) litter included all of the dead organic material above mineral soil in the surface layer, whereas Dimitrakopoulos (2002) supposedly consider litter only the freshly fallen leaves and spines. The small amount of litter in Mediterranean vegetation can be due to the fact that individual particles can remain on the plant after dying or they decay fast as they are small.

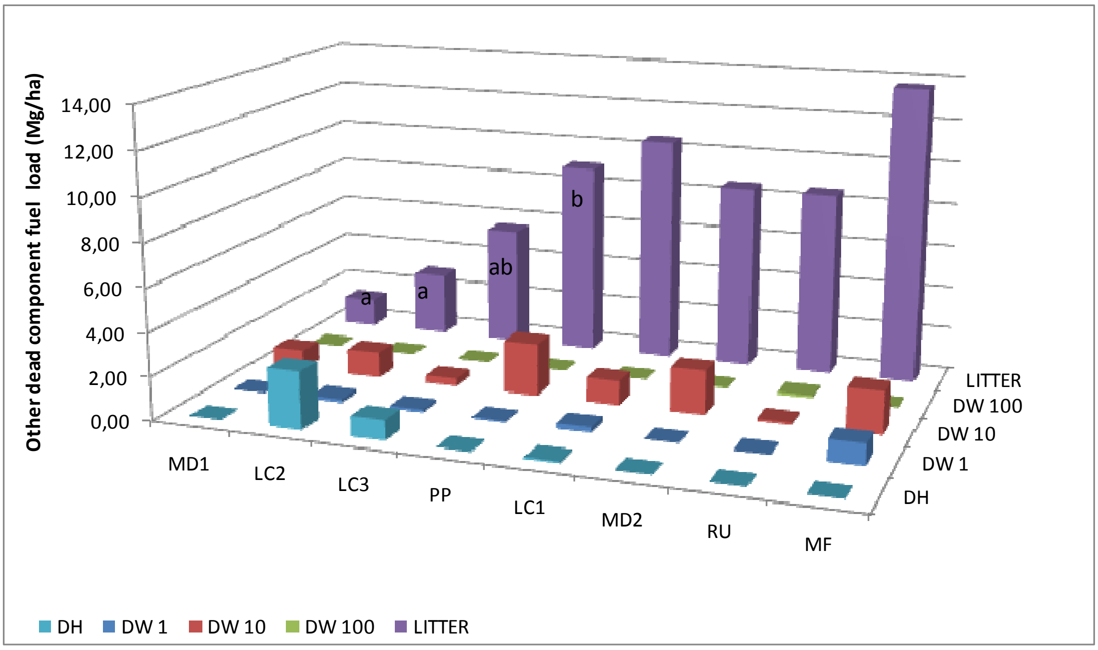


Figure 59 Litter and dead downed woody partitioning in the study areas. The litter load showed significant differences, at $p < 0.05$, only within the burned areas, marked with different letter

Table 33 Litter and dead downed woody in Mg ha^{-1} , diametric classes percentage partitioning on dead fuel load (in brackets and italics) (left part of the table); diametric classes percentage partitioning on total shrub fuel load (right part of the table)

	Total dead fuel load (Mg ha^{-1})					% on total fuel			
	Litter	DH	DW 1	DW 10	DW 100	Litter	DW 1	DW 10	DW 100
MD1	1.32 *(17.80%)*			0.89 *(12.07%)*		9.96		6.75	
LC2	2.93 *(19.26%)*	2.64 *(17.39%)*	0.14 *(0.94%)*	1.20 *(7.88%)*		13.51	0.66	5.53	
LC3	5.54 *(29.8%)*	0.91 *(4.9%)*	0.11 *(0.6%)*	0.35 *(1.9%)*		14.08	0.29	0.88	
PP	8.96 *(64.16%)*		0.06 *(0.40%)*	2.43 *(17.38%)*		25.96	0.16	7.03	
Average %	***32.76***	***11.15***	***0.65***	***9.80***		***15.87***	***0.37***	***5.05***	
LC1	10.51 *(63.43%)*	0.06 *(0.39%)*	0.23 *(1.41%)*	1.11 *(6.69%)*		28.42	0.63	3.00	
MD2	8.56 *(50.88%)*			2.03 *(12.08%)*	0.03 *(0.16%)*	24.09		5.72	0.08
RU	8.55 *(62.91%)*			0.10 *(0.75%)*	0.10 *(0.76%)*	15.48		0.18	0.19
MF	13.71 *(57.09%)*		0.96 *(3.99%)*	1.97 *(8.22%)*		26.67	1.86	3.84	
Average %	***58.58***	***0.39***	***2.70***	***6.93***	***0.46***	***23.67***	***1.25***	***3.19***	***0.07***

8.2.3. Characteristics of some shrubs

Considering the distribution between live and dead material in every species (Table 34), in area LC1, *A. unedo* was the only species with the dead fraction higher than the live. *P. angustifolia* dead percent on the total load was particularly small. In all burned areas, *M. communis* showed always a live percent higher than the dead material, whereas species as *C. monspeliensis* had a *live/dead* ratio relatively small. In the burned areas, moreover, *P. lentiscus* distinguished due to the live load smaller than the dead, except for PP, burned in the 1999; it was interesting notice that *C. humilis* showed always live values higher than necromass.

In Figure 60, the contribution of the single species to the shrub live load is considered. *P. lentiscus* was often surveyed, both in areas recently burned and in areas relatively intact, which due to its density yields a percent contribute remarkable. In areas LC3, MD1, and MD2, moreover, it was possible to detect that *C. humilis* concurred to the live load more than other species. Taking into account single species contribute to the dead load (Figure 61), in the unburned area, *M. communis, C. monspeliensis* and *C. spinosa* (when present) gave the main contribute (respectively 61%, 57%, and 44%), whereas in the burned areas the *P. lentiscus* contribution was predominant, varying from 18% in area 4 to the almost totality of dead material in area LC2. On the other hand *C. humilis*, highly present in areas LC3, MD1, and MD2, contributing to the live material with loads higher than 50%, participated to the dead percent with loads not superior to 34%; in particular in the area MD1, burned in the 2007, it contributed just with the 3%.

Table 34. Specific vegetational material distribution between live and dead

	% live	% dead
LC1		
Arbutus unedo	39.28	60.72
Cistus monspeliensis	57.16	42.84
Lonicera implexa	77.57	22.43
Myrtus communis	70.78	29.22
Phillyrea angustifolia	98.57	1.43
Pistacia lentiscus	89.69	10.31
LC2		
Calicotome spinosa	89.74	10.26
Chamaerops humilis	84.84	15.16
Cistus monspeliensis	100.00	0.00
Daphne gnidium	100.00	0.00
Myrtus communis	100.00	0.00
Pistacia lentiscus	38.20	61.80
LC3		
Chamaerops humilis	79.53	20.47
Myrtus communis	57.44	42.56
Pistacia lentiscus	23.66	76.34
PP		
Arbutus unedo	93.84	6.16
Calicotome spinosa	85.45	14.55
Cistus monspeliensis	73.62	26.38
Daphne gnidium	100.00	0.00
Lonicera implexa	100.00	0.00
Phillyrea angustifolia	97.90	2.10
Pistacia lentiscus	92.59	7.41
Quercus ilex	94.84	5.16
Rosmarinus officinalis	95.20	4.80

	% live	% dead
RU		
Calicotome spinosa	51.26	48.74
Cistus salvifolius	100.00	0.00
Erica arborea	72.57	27.43
Myrtus communis	83.60	16.40
Pistacia lentiscus	93.64	6.36
MD1		
Chamaerops humilis	95.57	4.43
Cistus monspeliensis	28.98	71.02
Daphne gnidium	95.58	4.42
Pistacia lentiscus	30.04	69.96
Rosmarinus officinalis	0.74	99.26
MD2		
Calicotome spinosa	97.11	2.89
Chamaerops humilis	83.92	16.08
Cistus monspeliensis	42.55	57.45
Daphne gnidium	72.15	27.85
Pistacia lentiscus	95.26	4.74
MF		
Arbutus unedo	88.52	11.48
Calicotome spinosa	27.87	72.13
Cistus monspeliensis	41.56	58.44
Cistus salvifolius	42.97	57.03
Erica arborea	88.86	11.14
Lonicera implexa	100.00	0.00
Myrtus communis	88.89	11.11

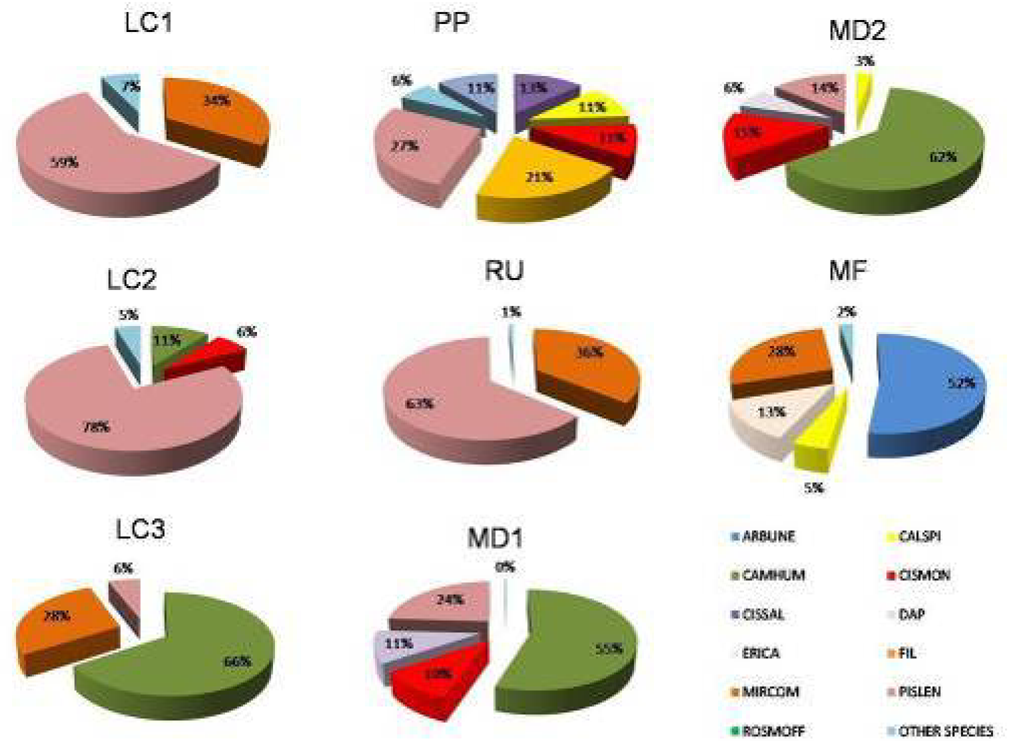


Figure 60. Single species contribute to the total shrub live load

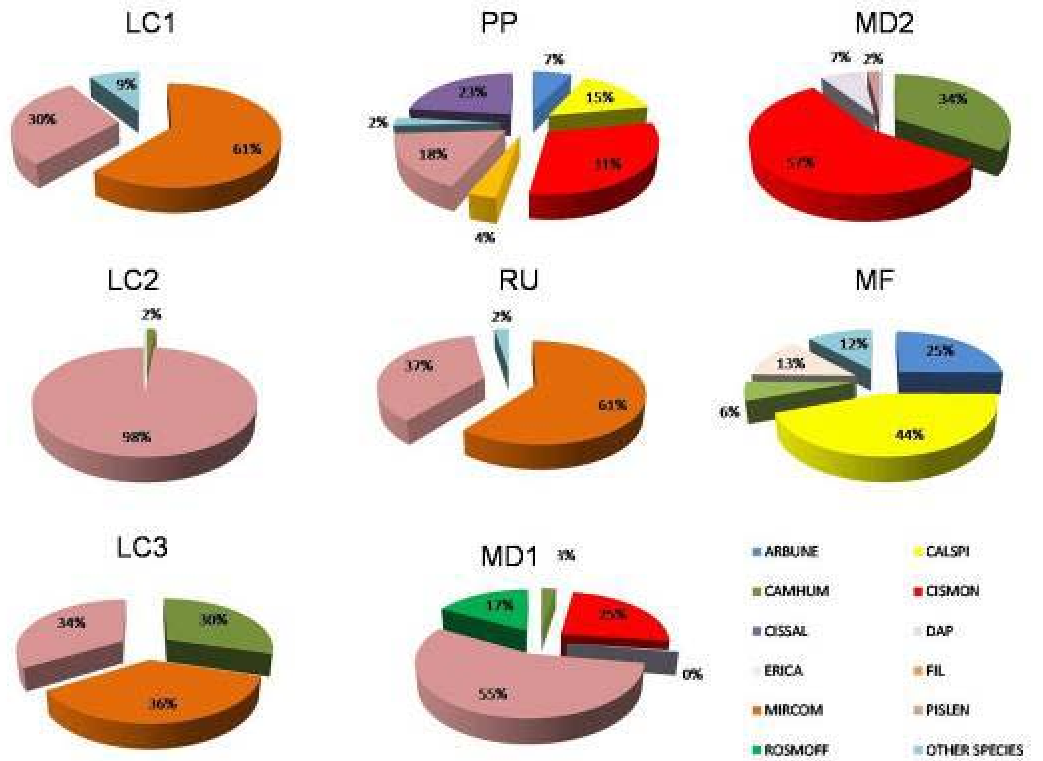


Figure 61. Single species contribute to the total shrub dead load

8.3. Analysis of the relationships between fuel complex properties and fuel load

With the aim to better understand which fuel parameter explained the most variation of several fuel components, all sampling plots, whether recently burned or not, were combined into a dataset, and the individual abilities of vegetation height, % cover, and the product of both (as a substitute for volume) to predict fuel load of each component were examined.

Table 35 showed the linear correlation coefficients among the variables and several fuel components. Total shrub (live + dead) fuel load was related to *Height* and *Cover* (r= 0.61, r= 0.65, p= 0.01), but the parameter seen to be most strongly correlated with was *Height*Cover*, (r= 0.75, p= 0.01); total available (live + dead <0.6 cm) shrub load was well related to *Cover* (r= 0.64, p= 0.01) and *Height*Cover* (r= 0.61, p= 0.01). Regarding the live components, live fine fuel (*L 1*), a component fundamental for the evaluation of fire behavior, was not highly correlated with the other fuel properties. *L 10* seen to be more correlated, in particular with *Height*Cover* variable (r= 0.74, p= 0.01). Among the dead components, *D 1*, very important to assess wildland fire behavior potential, did not have any relationship with other fuel properties, except with the *Cover* (r=0.50, p = 0.01), differently from the *Litter* that showed to be well correlated with the shrub *Height* (r= 0.65, p=0.01).

Table 35. Correlation matrix between fuel load components and the associated physical properties. TL: total live shrub load, TD: total dead shrub load, TS: total shrub (live and dead) load, TA: total available load, TP: total fuel load collected into the plot. **indicates significant correlation at the 0.01 level (2-tailed). *indicates significant correlation at the 0.05 level (2-tailed).

Components	*Cover*	*Height*	*Height * Cover*
L 1	0.61**	0.52**	0.63**
L 10	0.53**	0.64**	0.74**
L 100	0.38*	0.43**	0.53**
L 1000	0.15	-0.01	0.04
D 1	0.50**	0.17	0.32*
D 10	0.12	0.13	0.16
D 100	0.02	-0.03	-0.03
LH	0.10	-0.26	-0.18
DH	-0.46	-0.30	-0.32
DW1	0.07	0.39	0.37*
DW10	0.07	-0.07	-0.01
DW100	0.16	-0.03	0.03
Litter	0.51**	0.66**	0.71**
TL	0.63**	0.62**	0.75**
TD	0.23	0.15	0.21
TS	0.65**	0.61**	0.75**
TP	0.66**	0.66**	0.80**
TA	0.64**	0.47**	0.61**

Fine live fuel

Table 35 showed the results from the correlation analysis. The live component with diameter less than 0.6 cm was correlated (at the 0.01 level) with the main properties surveyed during the data collection, although it was not highly satisfying., The *Cover* and *Height*Cover* parameters mainly accounted for a significant amount of variance of the dependent variable (r=0.610, r=0.634, $p<0.01$), whereas the *Height* accounted only for the 0.516 ($p<0.01$).

Fine live load of all plots (here referred as live 1 hr total load) was considered as function of shrub height; in Table 36 the regression analysis parameters were summarized. The found power relation had value of R^2 0.49, $p<$ 0.001. In particular, Figure 62 showed that plots of the areas recently burned were little scattered, ranging from 0.04 to 2.14 kg m^{-2}, with height rarely up to 1.50 m, compared to plots of burned areas, showing height ranging from 0.81 to 2.3 m, with load varying from 0.23 to 1.93 kg m^{-2}. Across the burned sites, fine live fuel increased with increasing of the height. This trend was noticed also across the unburned sites, but for height above 1.5 m the *L 1* fuel appeared to became slightly constant. Therefore, the relation between height and fine live material in the burned areas was considered (Table 36, indicated with *b*), giving a significant R^2 (0.64, $p < 0.001$). The relation between height and fine live load in unburned areas was not significant.

These trends were attributable to the fire, because it destroyed principally the finest living material, when the heat produced by the burning litter and the dead material dried the living material enough to the point that it will burn. It is observable that several growing season after fire, the burned plots were characterized by different vegetation structures in response to fire, differences that were attenuated in the unburned areas (as showed in Figure 56).

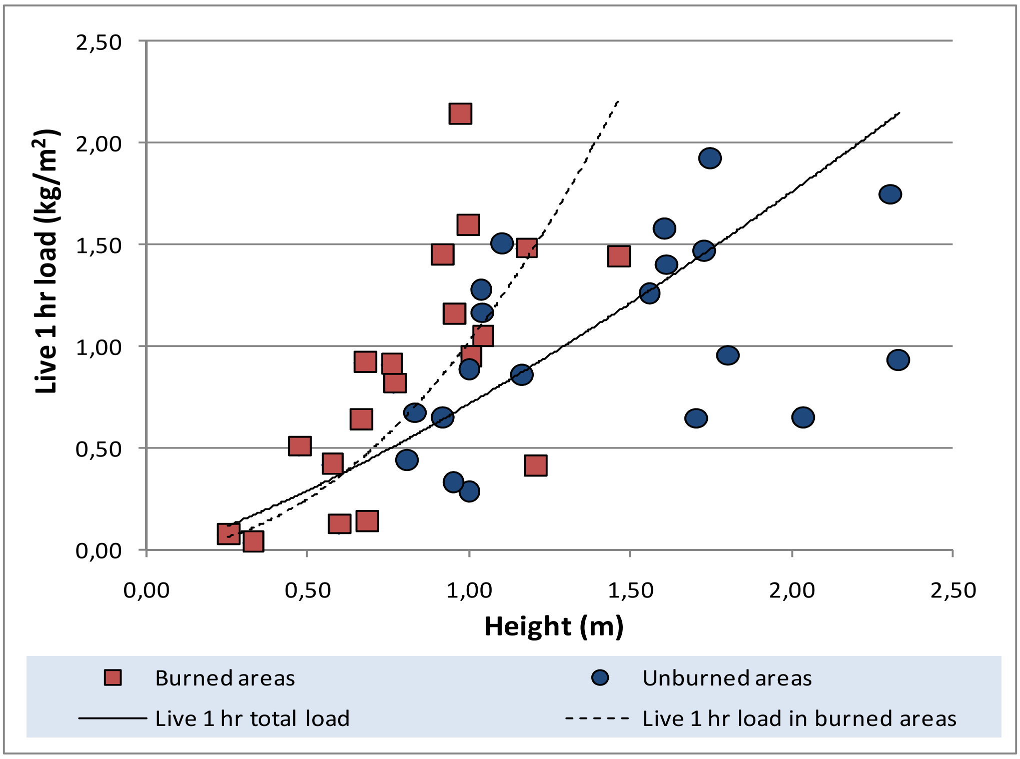


Figure 62. Fine live (L 1 hr) load as a function of shrub height (m), for the total dataset (continuous line) and the burned area sub-dataset (broken line)

Table 36. Power function regressions and coefficients to estimate fine live (L 1 hr) load, by total dataset, burned and unburned areas, as a function of shrub height (m)

Dependent variables	Model form	Constant and coefficients		df	R^2	MS	F	*p*
a)Total L 1 load	y= k*Height*^{b}	k: 0.720	SE: 0.075	1,37	0.489	0.425	35.504	< 0.0001
		b: 1.291	SE: 0.217					
b)L 1 hr load in burned plots	y=k*Height*^{b}	k: 1.022	SE: 0.190	1,17	0.635	0.496	26.617	0.001

Figure 63 looked at the relation between *Cover* of all plots in the inquired study areas and *L 1* load; in Table 37 were summarized the regression analysis parameters. In this case the found power relation had a value of R^2 0.43, $p< 0.001$. Across the burned sites, fine live fuel increased with increasing of the cover. This trend was noticed also across the unburned sites, but with a majority of plots with cover at 100%. Considering exclusively plot of the recently burned areas, the found relation, indicated with *b* in Table 37, gave a value of R^2 unsatisfactory (0.41, p <

0.005). The relation between cover and fine live load in unburned areas was not significant.

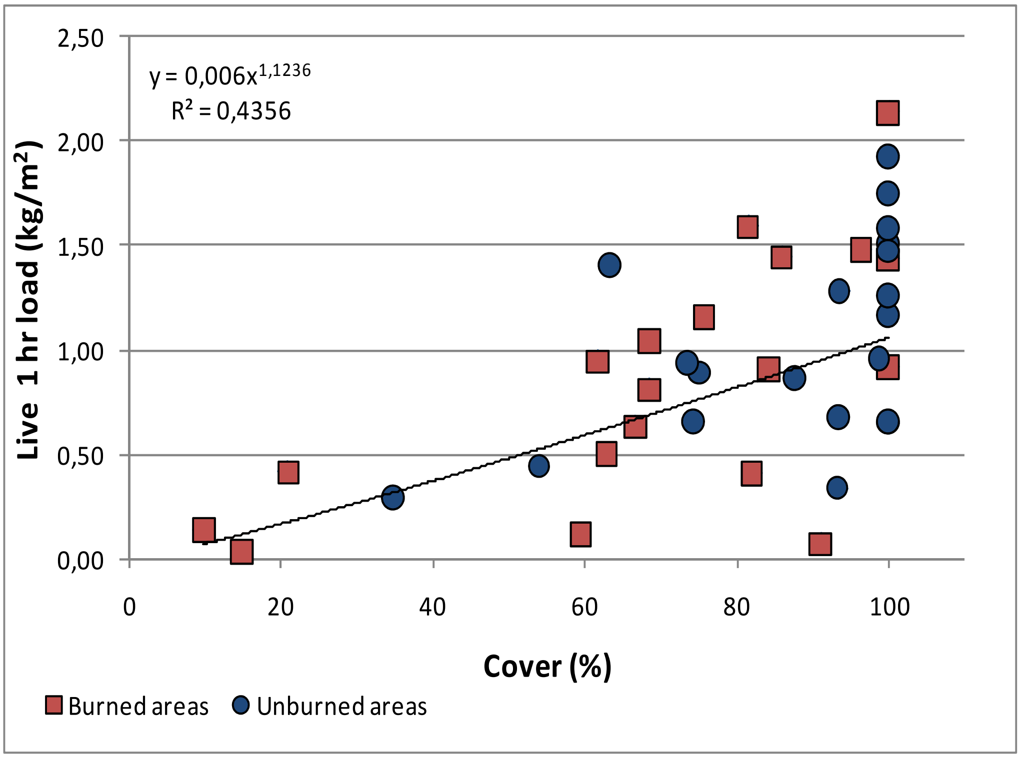


Figure 63. Fine live (L 1 hr) load as a function of shrub cover (%), for the total dataset (continuous line)

Table 37. Power function regressions and coefficients to estimate fine live (L 1 hr) load, by total dataset, burned and unburned areas, as a function of shrub cover (%)

Dependent variables	Model form	Constant and coefficients		df	R^2	MS	F	*p*
a)Total L 1 load	y= k*Cover* ^{b}	k: 0.006	SE: 0.005	1,37	0.436	0.470	28.553	<0.0001
		b: 1.124	SE: 0.210					
b)L 1 hr load in burned plots	y= k*Cover* ^{b}	k: 0.007	SE: 0.009	1,17	0.408	0.806	11.714	0.003

The other independent variable that in Table 35 accounted for a significant amount of variance of the dependent variable was *Height*Cover*. Fine live load of all plots was considered as a function of *Height*Cover* (Figure 64). The value of R^2 was 0.63, at $p < 0.001$. In this case, fine live fuel increased with increasing of the *Height*Cover* parameter, across both the burned sites and the unburned areas.

However, taking into account only recently burned plots, the R^2 value was 0.60 (p< 0.001), whereas in the unburned areas was 0.48, at p< 0.005 (Table 38).

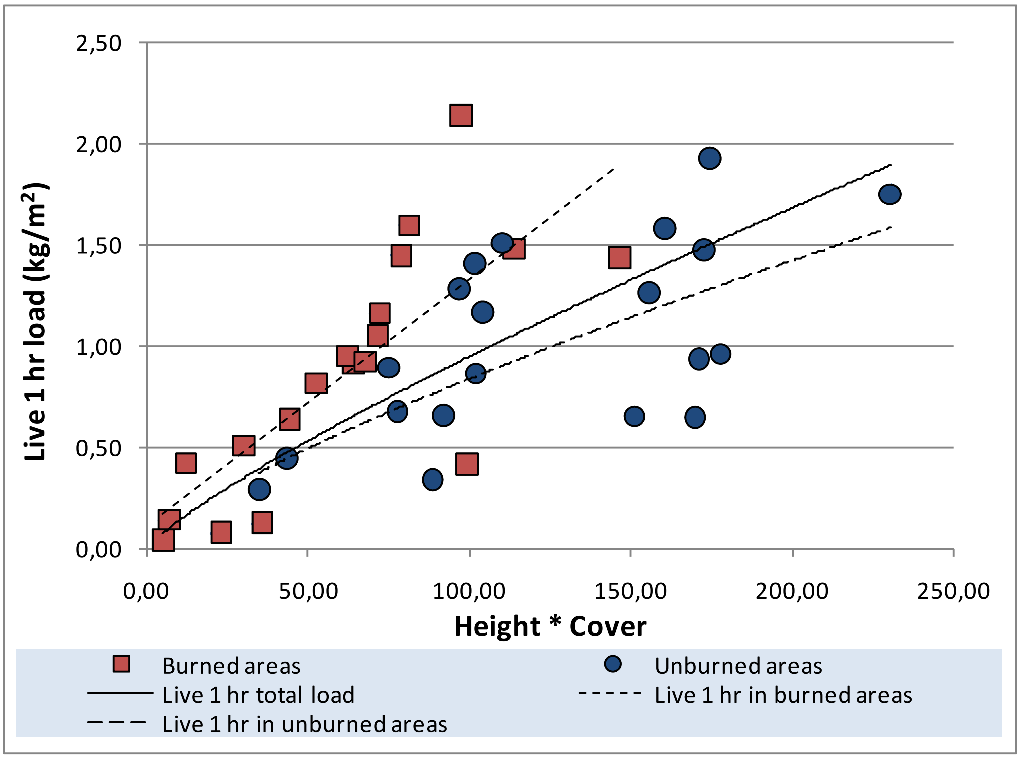


Figure 64. Fine live (L 1 hr) load as a function of shrub height (m) and cover (%), for the total dataset (continuous line), burned areas (small dotted line) and unburned areas (large dotted line) subsets

Table 38. Regressions and coefficients to estimate fine live (L 1 hr) load, by total dataset, burned and unburned areas subsets, as a function of shrub height (m) and cover (%)

Dependent variables	Model form	Constant and coefficients		df	R^2	MS	F	*p*
a)Total L 1 load	y= k*Height* * $Cover^b$	k: 0.021	SE: 0.010	1.37	0.634	0.305	64.041	<0.0001
		b: 0.826	SE: 0.103					
b)L 1 load in burned plots	y=k +*Height* * Cover	k: 0.113	SE: 0.170	1.17	0.604	0.147	25.905	<0.0001
		b: 0.012	SE: 0.002					
c)L 1 load in unburned plots	y= k*Height* * $Cover^b$	k: 0.025	SE: 0.022	1.18	0.477	0.160	16.437	0.001
		b: 0.763	SE: 0.188					

Dead fuel

Dead material, smaller than 0.6 cm, is important in influencing ignitability, fire development and fire spread rates in shrub dominated landscapes. Therefore, it was considered interesting to show that this component appeared to not have any relationship with the fuel properties, except with cover (r=0.498, p<0.01). Figure 65 showed two trends: across the burned areas there was a slightly increase of fine dead material with the *Height,* whereas the opposite trend was recognizable across all the plots unburned. Several Authors (McCaw, 1997; Keeley and Fotheringham, 2002) suggested that the proportion of dead fuel varies with height, but in this study the relation between *Height* and D 1 was not significant.

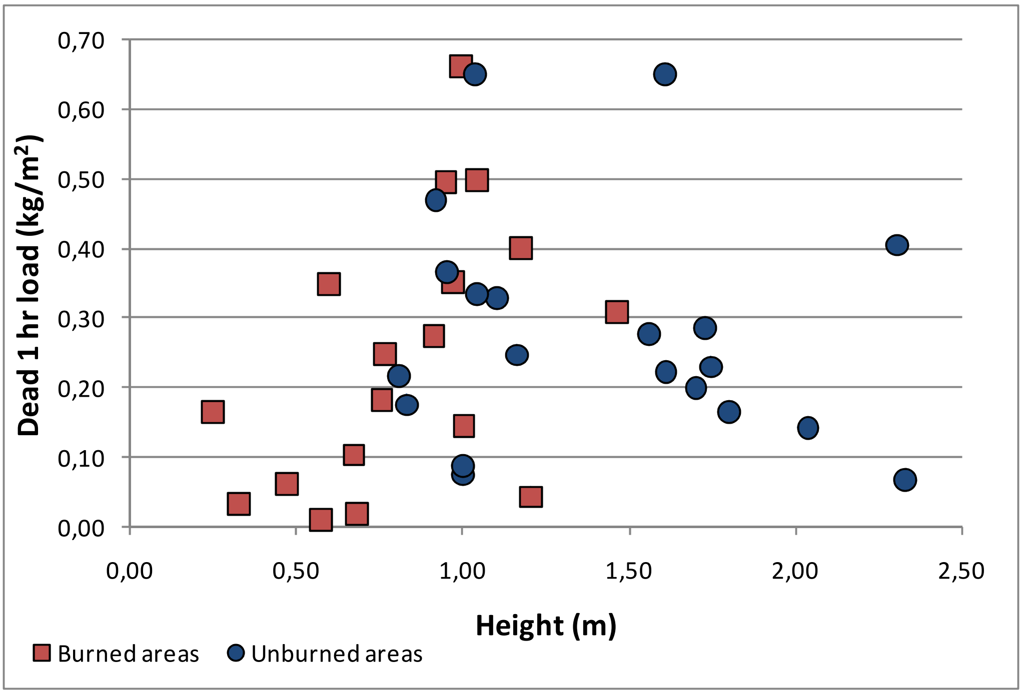


Figure 65. Fine dead (D 1 hr) load as a function of shrub height (m)

Considering the *Cover,* the relation found ($R^2 = 0.55$) was significant at $p < 0.001$. Figure 66 showed the increase of fine necromass increasing the *Cover*, in particular across the burned areas ($R^2 = 0.57$, $p < 0.001$). The relation between cover and fine dead load in unburned areas was not significant.

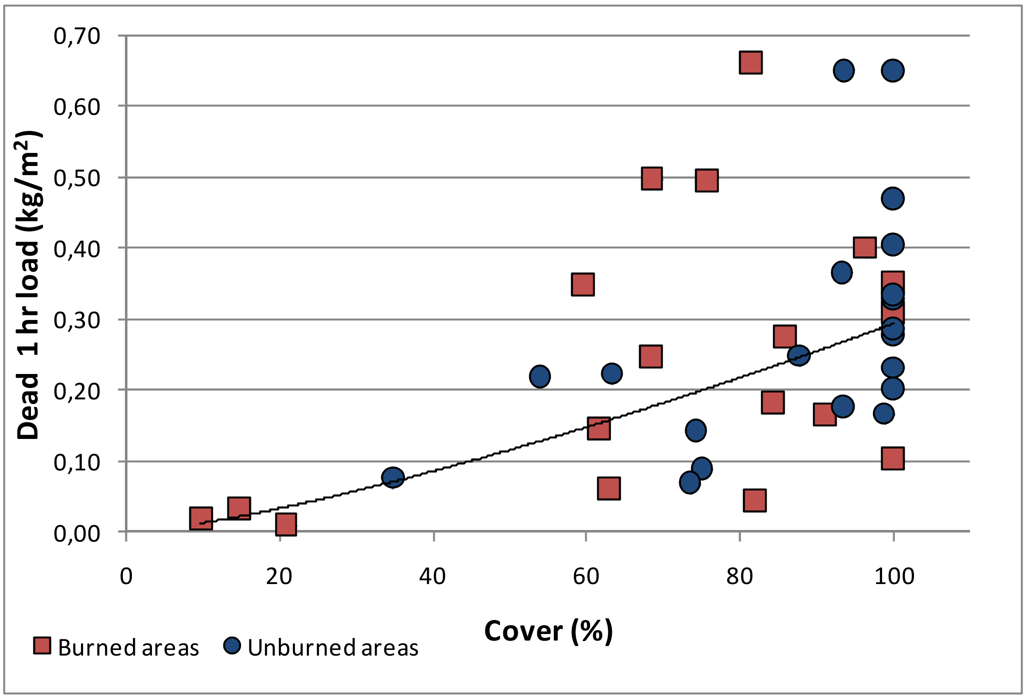


Figure 66. Fine dead (D 1 hr) load as a function of cover (%), for the total dataset (continuous line)

Table 39. Power function regressions and coefficients to estimate fine dead (D 1 hr) load, by total dataset, burned and unburned areas, as a function of cover (%)

Dependent variables	Model form	Constant and coefficients		df	R^2	MS	F	*p*
a)Total D 1 load	y= $kCover^b$	k: 0.001	SE: 0.001	1, 36	0.548	0.437	43.608	<0.0001
		b: 1.338	SE: 0.203					
b)D1 load in burned plots	y= $kCover^b$	k: 0.001	SE: 0.001	1, 15	0.574	0.714	20.214	<0.0001

Available fuel load

Available fuel, composed by live and dead leaves and fine branches smaller than 0.6 cm, is a component not used as input in the fuel model fire behaviour. This is fuel readily available for consumption, thus very important for fire spread and fire intensity. Results of the correlation analysis indicated that total available shrub load (burned and unburned areas load) was well related to *Cover* (r= 0.64, p< 0.01) and with *Height*Cover* (r= 0.61, p< 0.01); nevertheless, in a preliminary regression analysis also the *Height* was considered (Figure 67), showing a R^2 value of 0.43 (p< 0.001). In particular, the relation between *Height* and available fuel in the burned areas was considered, giving a significant R^2 (0.56, p < 0.001) (Table 40).

Considering the other two variables, *Cover* explained the 59% of the observed variation (p< 0.001) (Table 41), whereas *Height*Cover* accounted for a significant amount of variance of the dependent variable (70%, p<0.001): total available fuel load increased with increasing of *Height*Cover* parameter, across both the burned sites and unburned areas; however taking into account only the recently burned plots, the R^2 value was 0.80 (p< 0.001), whereas in the unburned areas was 0.45, at p< 0.005 (Table 42).

Regarding the best model found between total available fuel load and a shrub parameter, equation *a* in Table 42, informal analysis of the data using normal P-P plots (Figure 70) and scatterplot (Figure 71) revealed no serious threats to the assumption of normality and to the underlying distributional assumptions of residuals of the dependent variable. In Figure 71, although there were several points that might be outliers, the homogeneity of variance assumption did not appear to be substantially violated. Thus, although the data departed somewhat from the assumptions of normality and homogeneity of variance, they did not signal any serious violations of these assumptions.

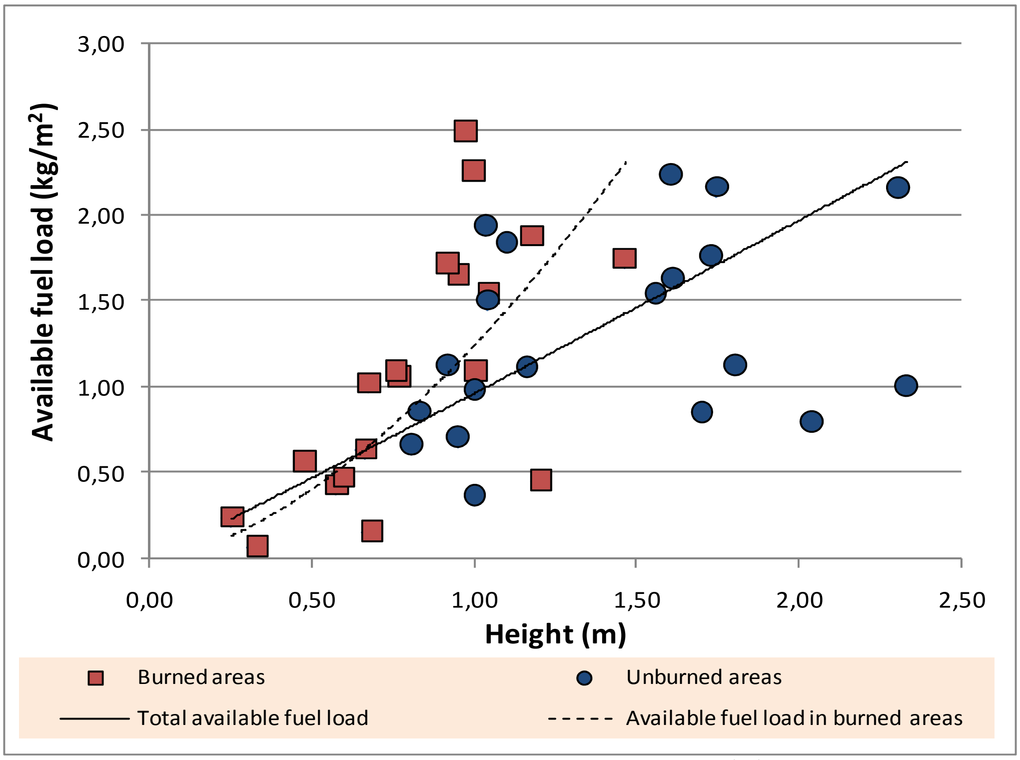


Figure 67. Available fuel load as a function of shrub height (m), for the total dataset (continuous line) and burned areas subset (small dotted line)

Table 40. Power function regressions and coefficients to estimate available fuel load, by total dataset, burned and unburned areas, as a function of shrub height (m)

Dependent variables	Model form	Constant and coefficients		df	R^2	MS	F	*p.*
a)Total available fuel load	$y = k\,Height^b$	k:0.963	SE:0.092	1,37	0.425	0.354	27.397	<0.0001
		b:1.035	SE:0.198					
b)Available fuel load in burned plots	$y = k\,Height^b$	k: 1.248	SE: 0.226	1,17	0.562	0.431	21.777	<0.0001
		b:1.622	SE: 0.348					

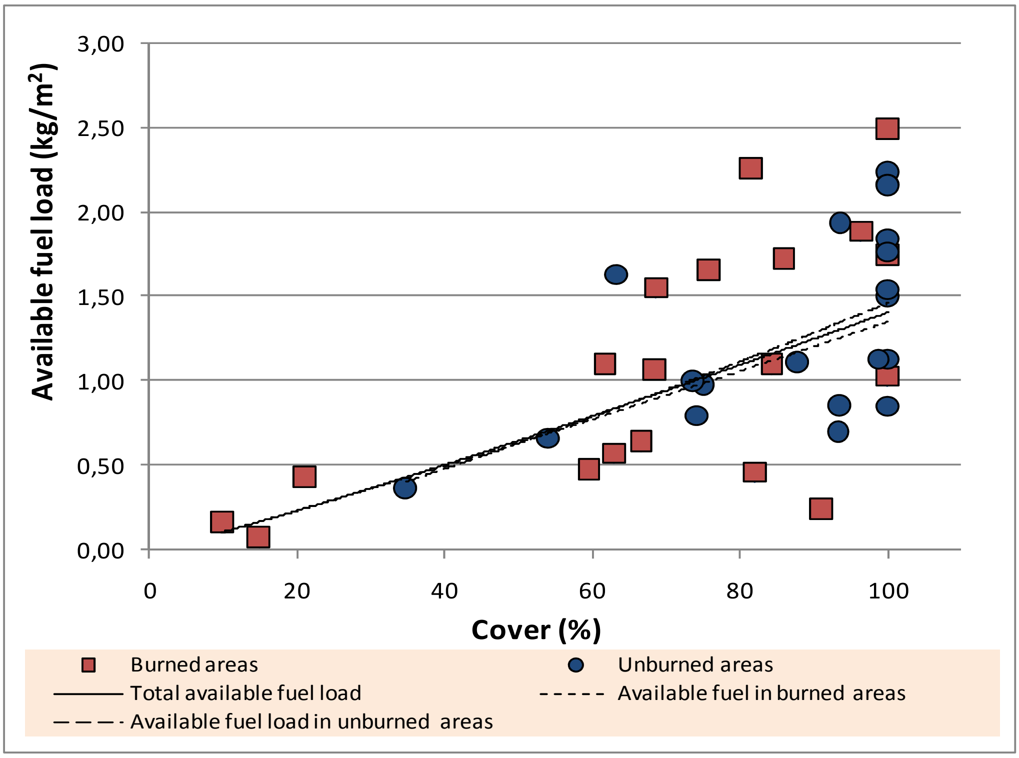


Figure 68. Available load as a function of cover (%), for the total dataset (continuous line), burned areas (small dotted line) and unburned areas (large dotted line) subsets

Table 41. Power function regressions and coefficients to estimate available fuel load, by total dataset, burned and unburned areas, as a function of shrub cover (%)

Dependent variables	Model form	Constant and coefficients		df	R^2	MS	F	*p*
a)Total available fuel load	y = k*Cover*^{b}	k:0.008	SE:0.005	1,37	0.587	0.255	52.513	<0.0001
		b:1.122	SE:0.155					
b)Available fuel load in burned plots	y= k*Cover*^{b}	k: 0.009	SE: 0.009	1,17	0.574	0.419	21.935	<0.0001
		b:1.088	SE: 0.227					
c) Available fuel load in unburned plots	y= k*Cover*^{b}	k: 0.006	SE:0.007	1,18	0.480	0.127	16.637	0.001
		b: 1.208	SE:0.0296					

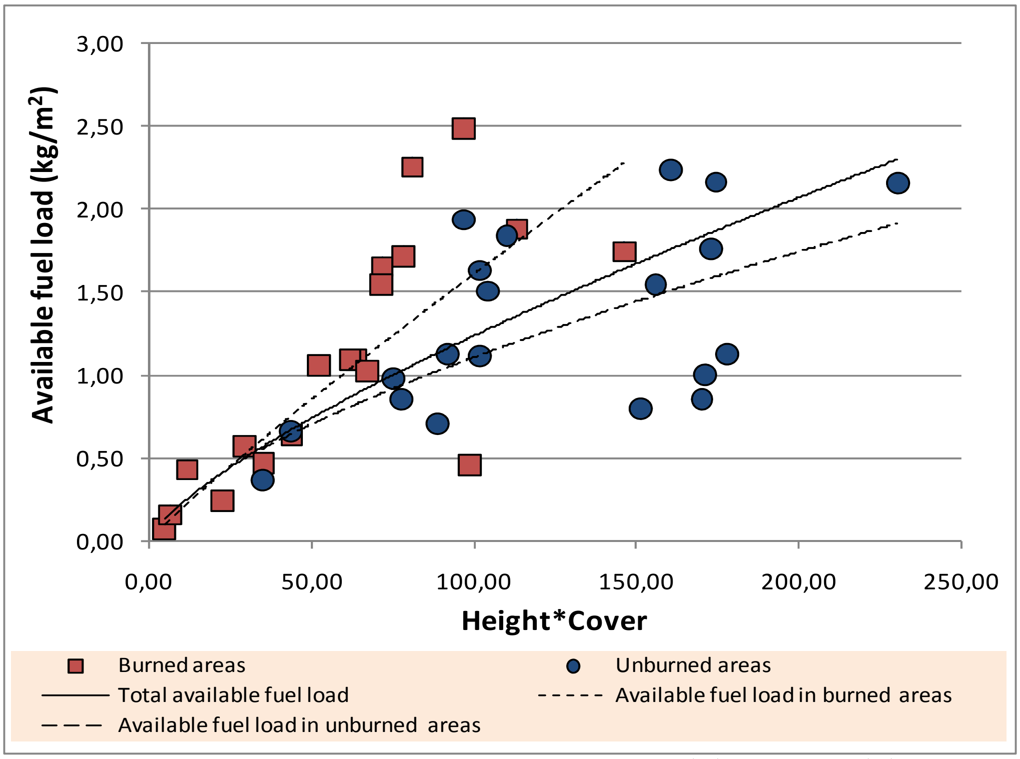


Figure 69 Available fuel load as a function of shrub height (m) and cover (%), for the total dataset (continuous line), burned areas (small dotted line) and unburned areas (large dotted line) subsets

Table 42 Power function regressions and coefficients to estimate available fuel load, by total dataset, burned and unburned areas, as a function of shrub height (m) and cover (%)

Dependent variables	Model form	Constant and coefficients		df	R^2	MS	F	*p*
a) Total available fuel load	y = k*Height*Cover* ^{b}	k:0.040	SE:0.014	1,37	0.696	0.188	84.532	<0.0001
		b:0.745	SE:0.081					
b) Available fuel load in burned plots	y= k*Height*Cover* ^{b}	k: 0.0912	SE: 0.112	1,17	0.797	0.199	66.814	<0.0001
		b:0.024	SE: 0.011					
c) Available fuel load in unburned plots	y= k*Height*Cover* ^{b}	k: 0.053	SE:0.047	1,18	0.447	0.135	14.543	0.001
		b: 0.659	SE:0.173					

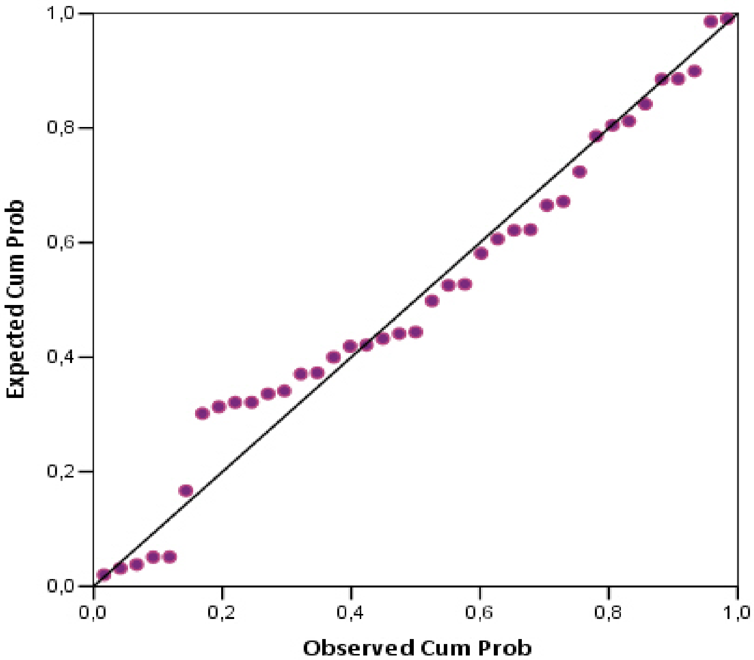


Figure 70. Normal P-P plots of total available fuel load residuals

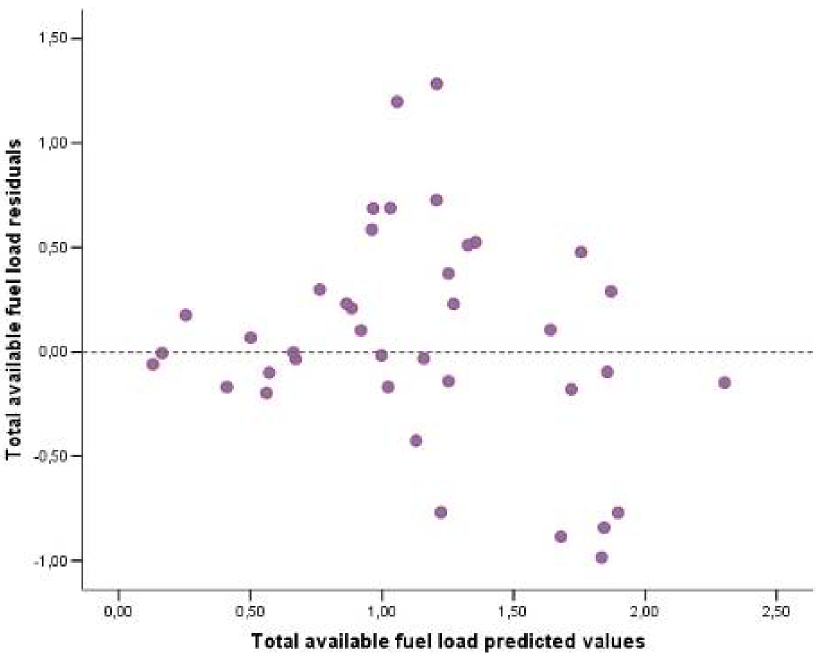


Figure 71. Scatterplot of total available fuel load residuals

Total shrub fuel load

In Figure 72 the relation between total shrub fuel load and *Height* of all plots in the inquired study areas was considered. The power relation had a value of R^2 0.52, $p < 0.001$. In particular, Figure 72 showed that the plot of the areas recently burned were less scattered compared to the plot of the burned areas. Across the burned sites, total shrub fuel load increased with height increasing. This trend was noticed also across the unburned sites, but for height above 1.5 m total shrub fuel load become slightly constant. The relation between height and fuel load in the burned areas was considered, giving a significant R^2 (0.60, $p < 0.001$) (Table 43). The relation between height and fine live load in unburned areas was not significant.

The regression analysis parameters of the relation between C*over* and total shrub fuel load (Figure 73) were summarized in Table 44. *Cover* explained the 63% of the observed variation, $p < 0.001$, and in particular from figure it was observable that across the burned sites, total shrub fuel load increased with increasing of the cover.

*Height*Cover* accounted for a significant amount of variance of the dependent variable (78%, $p<0.001$) (Table 45): total shrub fuel load increased with increasing of *Height*Cover* parameter, across both the burned sites and unburned areas; however taking into account only the recently burned plots, the R^2 value was 0.84 ($p < 0.001$), whereas in the unburned areas was 0.66, at $p < 0.001$.

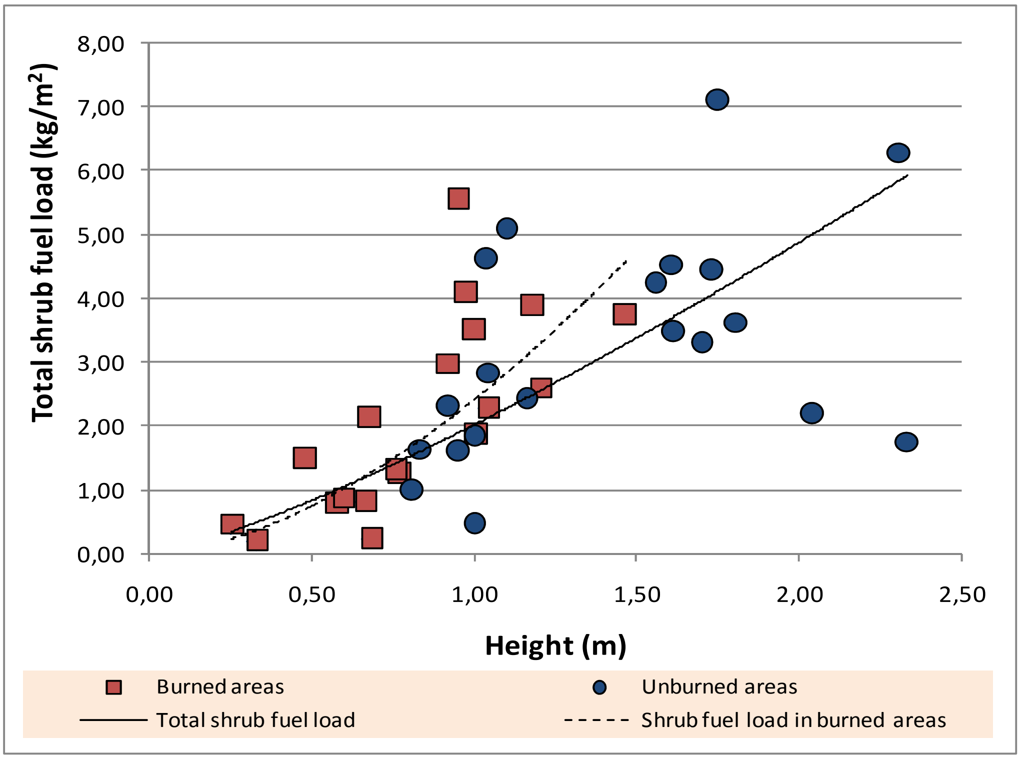


Figure 72. Total shrub load as a function of shrub height (m) for the total dataset (continuous line) and burned areas (small dotted line)

Table 43. Power function regressions and coefficients to estimate total shrub load, by total dataset, burned and unburned areas, as a function of shrub height (m)

Dependent variables	Model form	Constant and coefficients		df	R^2	MS	F	*p.*
a)Total shrub fuel load	y = k*Height*^{b}	k:2.267	SE:0.195	1,37	0.520	0.362	40.160	<0.0001
		b:1.167	SE:0.200					
b)Shrub fuel load in burned plots	y= k*Height*^{b}	k: 2.434	SE: 0.414	1,17	0.604	0.382	25.895	<0.0001
		b:1.666	SE: 0.327					

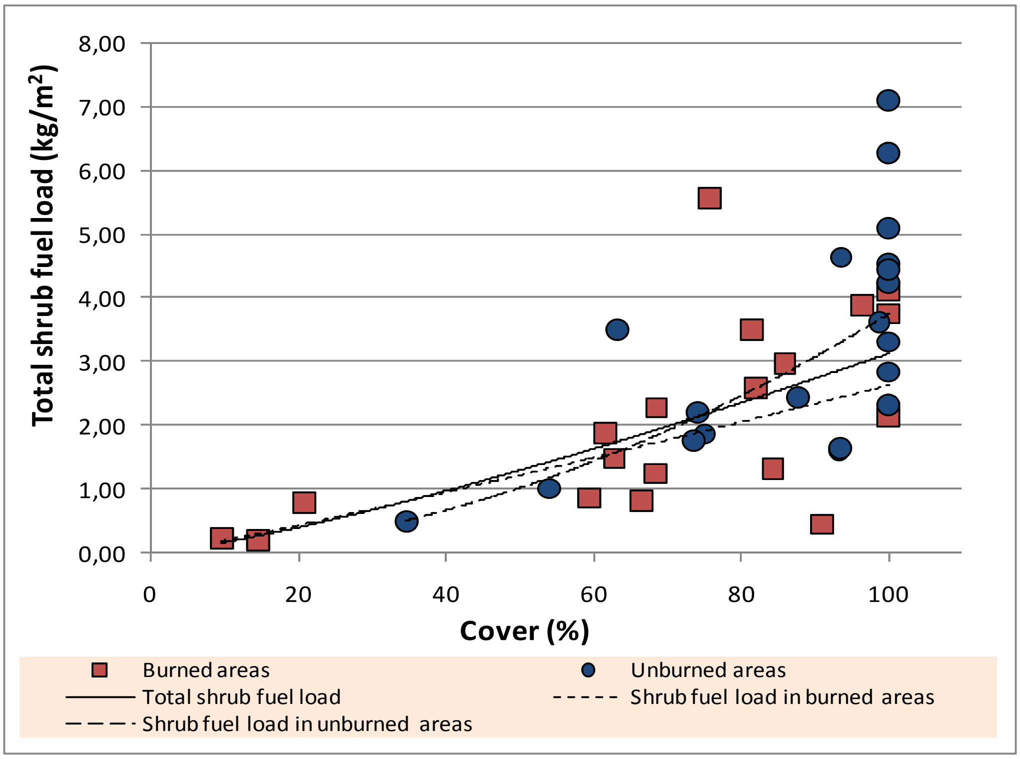


Figure 73. Total shrub load as a function of shrub cover (%), for the total dataset (continuous line), burned areas (small dotted line) and unburned areas (large dotted line) subsets

Table 44. Power function regressions and coefficients to estimate total shrub load, by total dataset, burned and unburned areas, as a function of shrub cover (%)

Dependent variables	Model form	Constant and coefficients		df	R^2	MS	F	*p*
a)Total shrub fuel load	y= k *Cover*^{b}	k:0.009	SE:0.006	1,37	0.617	0.289	59.700	<0.0001
		b:1.273	SE:0.165					
b)Shrub fuel load in burned plots	y= k *Cover*^{b}	k: 0.017	SE: 0.015	1,17	0.596	0.389	25.096	<0.0001
		b:1.098	SE: 0.219					
c)Shrub fuel load in unburned plots	y= k *Cover*^{b}	k:0.001	SE:0.001	1,18	0.627	0.168	30.200	<0.0001
		b:1.875	SE:0.341					

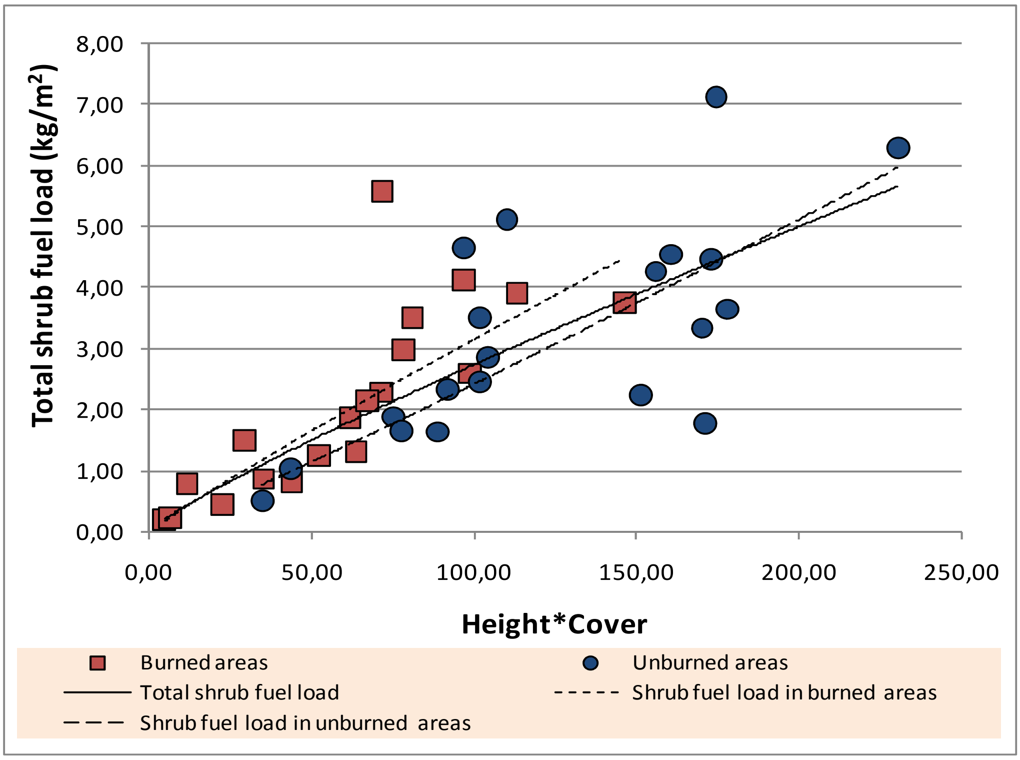


Figure 74. Total shrub load as a function of shrub height (m) and cover (%), for the total dataset (continuous line), burned areas (small dotted line) and unburned areas (large dotted line) subsets

Table 45. Power function regressions and coefficients to estimate total shrub load, by total dataset, burned and unburned areas, as a function of shrub height (m) and cover (%)

Dependent variables	Model form	Constant and coefficients		df	R^2	MS	F	*p*
a)Total shrub fuel	y= *kHeight*Cover^b*	k:0.048	SE:0.016	1,37	0.783	0.164	133.67	<0.0001
		b:0.875	SE:0.076					
b)Shrub fuel load in burned plots	y= *kHeight*Cover^b*	k: 0.044	SE: 0.017	1,17	0.839	0.155	88.652	<0.0001
		b:0.927	SE: 0.098					
c)Shrub fuel load in unburned plots	y= *kHeight*Cover^b*	k:0.016	SE:0.014	1,18	0.655	0.155	34.240	<0.0001
		b:1.085	SE:0.185					

The assumption of normality of the best model found among total shrub fuel load and shrub parameters, equation *a* in Table 45, was inspected through normal P-P plots (Figure 75), which showed on the *x*-axis the actual proportion of residual values and on the y-axis the predicted cumulative proportion based on a normal distribution. Even if the points did not fall perfectly on the diagonal line, examining the P-P plot substantial departure from normality was not exhibited. Also in Figure 76, although there were several points that may be outliers, the homogeneity of variance assumption did not appear to be substantially violated.

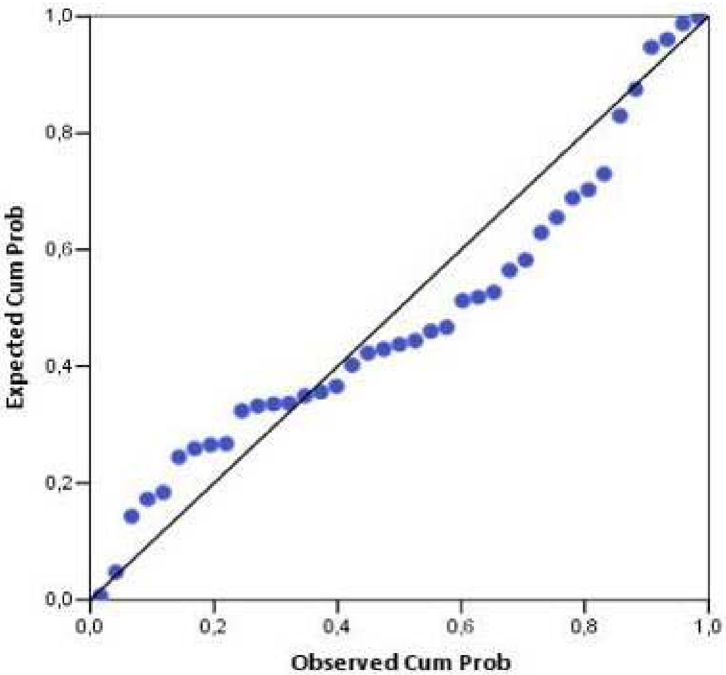


Figure 75. Normal PP plot of total shrub fuel load residual

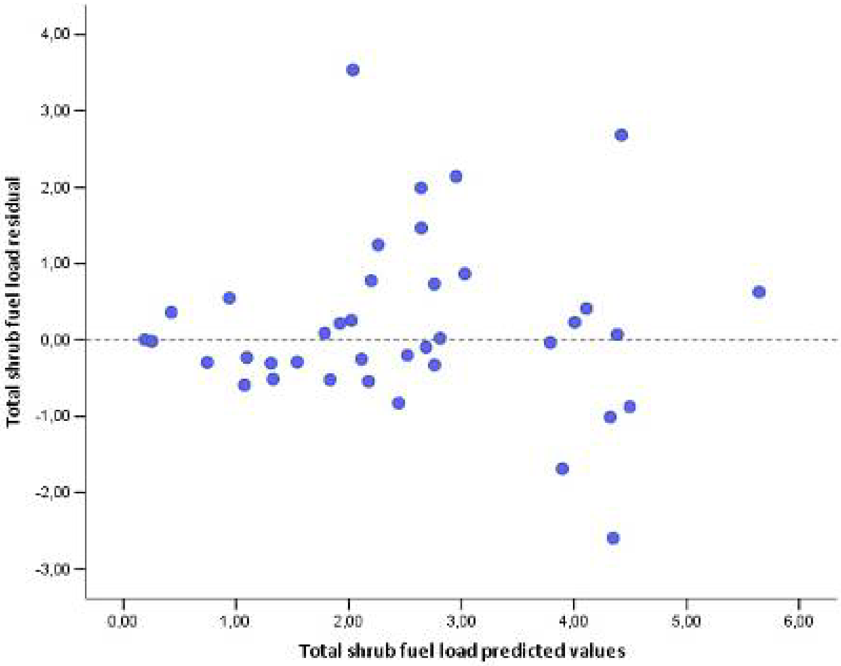


Figure 76. Scatterplot of total shrub fuel load residuals

Most equation predicted fuel or aboveground fuel load for individual shrubs from the measurement of stem (e.g. Brown, 1976; Buech and Rugg, 1989) or crown related (e.g. Lyon, 1968; Frandsen, 1983) variables; other authors combined both types of variables in the same equation (e.g. Hutchings and Mason, 1970; Elliot and Clinton, 1993). Usually fuel height is a remarkable input for models as it is easier to measure than other variable, such as mass and density (Fernandes, 2001), often in conjunction with a measure of cover. In several studies the apparent volume or the product between vegetation height and % cover, as a substitute of the volume, was used as independent variables for estimating the aboveground fuel load of several species (Pereira, 1995; Usò et al., 1996; Fernandes and Rego, 1998b; Saglam et al, 2008). Moreover, these authors presented the use of non-linear regression to predict fuel load of several species. Usò and colleagues (1996) examined exponential equation and power function regression, showing that for several species of Spanish Mediterranean maquis the correlation coefficient for the exponential equation (r=0.95) was higher than the power-function equation (r = 0.76). Pereira et al. (1995), found the power-function equation with a correlation coefficient r = 0.73. Fernandes and Rego (1998b) derived equation to predict total fuel load by size class at the stand level, using overall stand structure (height*cover) as the independent variable (Table 46).

Table 46. Power function $y=b_0(C*h)^{b_1}$ to estimate fuel loads (Mg ha-1) in *Chamaespartium tridentatum* and *Erica umbellata* shrubland, where *C* is vegetation ground cover (%) and *h* is the average community height (m)
From Fernandes and Rego (1998b).

Class	Coefficient estimates and standard errors of the estimates		Adj. r^2	syx
	b_0	b_1		
Total fuel				
[1]<2.5 mm	0.461 (0.222)	0.828 (0.136)	0.92	0.09
2.5-6.0 mm	0.010 (0.005)	1.477 (0.150)	0.92	0.02
>6.0 mm	0.257×10^{-4} (0.834×10^{-4})	2.931 (0.829)	0.88	0.03

Also in this study, the best results were obtained describing fine live, total available and total shrub fuel loads as a function of the product between vegetation height and % cover, using power function regression. The equations presented showed R^2 slightly smaller than the studies presented above, but it must be considered that they were obtained considering maquis formation community, instead single shrub species, and in addiction burned and unburned were combined into one dataset.

Considering the coefficient of determination of the burned sites exclusively, the R^2 was higher than the unburned sites. This was due probably to different vegetation structures in response to fire, which increases the amount of light and water availability, decreasing intra- and inter-specific competition (e.g. Trabaud, 1977; Reinhart and Menges, 2004), whereas into the unburned areas the differences were attenuated.

The relations between height and the fuel component considered in this study were not highly satisfying, and also in this case the R^2 found considering the burned sites was higher than the unburned sites. The results showed that height increased rapidly in the first few years after fire, before reaching a steady state due to competition for light and water. Shrub cover had similar trends, with a rapid increase in the first few years after fire before plateauing to a steady state. This could be the result of several causes: for example, different species may achieve different heights on the same site because the rate of shrub height increase could depend on the regeneration type, with individual plants of the same species regenerating much slower when growing from seed than when resprouting (Horton and Kraebel, 1955).

Litter

The heat produced by the burning litter fuel can be important in the ignition and sustainability of fire in shrub dominated communities (McCaw, 1991a; 1995; 1997). Nevertheless the litter is a very important addition to the maquis floor, it is rarely reported, even though it can be one of the most important components of the total fuel for fire behaviour prediction, because it can contribute to fire spread (Albini, 1976; Rothermel, 1972).

A correlation analysis was performed to select the independent variables better correlated with litter load. Shrub height, volume and cover, litter height and cover, fine fuel live and dead were considered. In particular, firstly the correlation analysis was performed using data from all the study areas; thus, detailed analysis was conducted for burned and unburned areas.

Table 47 showed the results of correlation analysis. The litter load was well correlated (at the 0.01 level) with the main properties surveyed during the data collection. Although each independent variable alone correlated significantly with the dependent variable, mainly litter height and cover accounted for a significant amount of unique variance of the dependent variable. Therefore firstly, the litter properties, cover and height, were discussed.

Table 47. Correlation matrix among litter and several parameter collected during the survey. DV, dependent variable; ** Correlation is significant at the 0.01 level (2-tailed); * Correlation is significant at the 0.05 level (2-tailed)

	Litter (DV)	*Shrub height*	*Shrub cover*	*Shrub volume*	*Litter height*
Shrub height	**0.661****				
Shrub cover	**0.509****	0.368			
Shrub volume	**0.632****	0.935**	0.401*		
Litter height	**0.717****	0.755**	0.390	0.809**	
Litter cover	**0.718****	0.371	0.465*	0.412*	0.291
Live 1 hr	**0.536****				
Dead 1 hr	**0.322**				

The linear relation between the litter height (its thickness in cm) and the relative load into the plots gave significant value of R^2 (0.51), at $p< 0.001$ (Figure 77). The elevated thickness of some plots (belonging to area MF, more than 25 years old) moved them away from the more compact group. Therefore, the plots recently burned were considered (Figure 78), providing a linear regression that supplies a satisfactory R^2 (0.60), with $p < 0.001$ (equation c in Table 48). In the areas recently burned the litter height was maintained of approximately 1 cm (Figure 78) while the other areas differentiated from this trend. An analysis of each area was made, showing *M. communis*, *P. lentiscus*, and *Cistus* spp contributed remarkably to the fuel load

The relation between litter height and litter load in unburned areas was not significant. It is probable therefore to assert that, in the first case, the litter deposition was affected by the fire and its strong effect of disturbance, while in the areas unburned other phenomena interacted with litter deposition.

The relations between shrub height and the litter load, and litter height were also considered. Figure 79 showed that with the increasing of the shrub height there was also an increasing of the litter load, as well as the litter thickness (Figure 80).

Several studies affirmed that the dense structure of shrubs and other plants presents in Mediterranean vegetation could prevent larger fallen dead material from reaching the ground, leaving it suspended, but in this study (Figure 81) higher litter load was in conjunction with dense and high vegetation, in particular mature maquis, at least more than 20 years old.

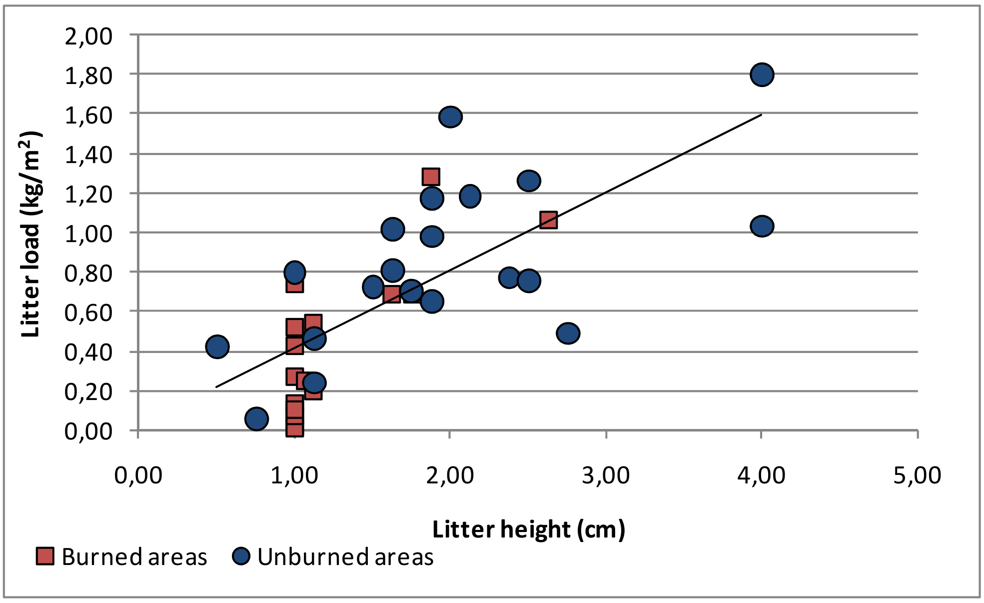


Figure 77. Litter load as a function of litter height (cm) for the total dataset

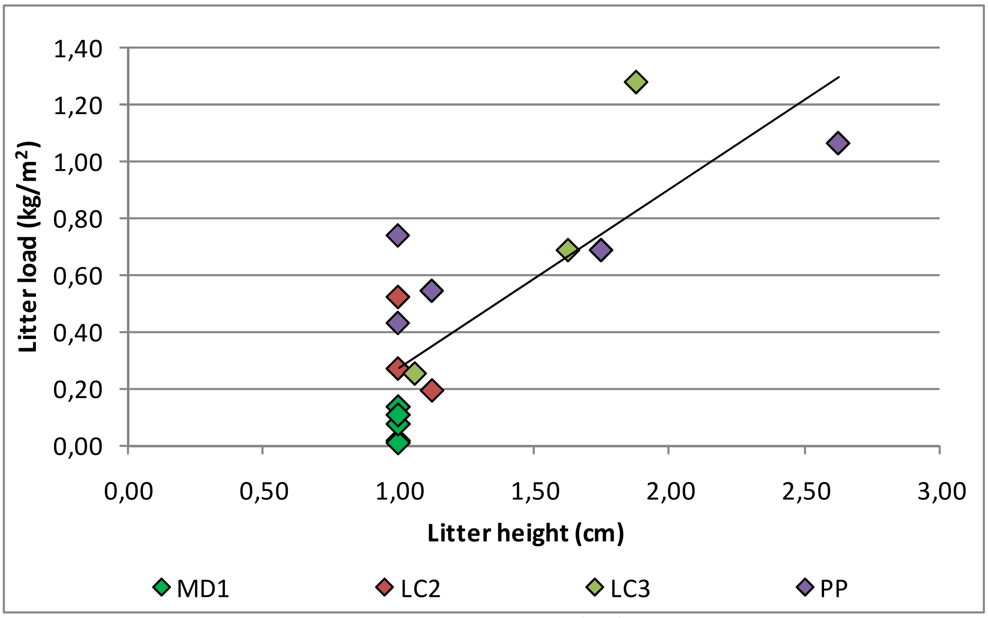


Figure 78. Litter load as a function of litter height (cm) for the burned areas sub-dataset

Table 48. Power function regressions and coefficients to estimate litter load, by total dataset, burned and unburned areas, as a function of litter height (cm)

Dependent variables	Model form	Constant and coefficients		df	R^2	MS	F	*p*
a)Total Litter load	y= b(height) + k	k: 0.018	SE: 0.120	1,34	0.515	0.102	36.050	<0.0001
		b: 0.394	SE: 0.066					
b)Litter load in burned plots	y= b (height) – k	k: -0.352	SE: 0.182	1,18	0.602	0.061	21.220	<0.0001
		b: 0.627	SE: 0.136					

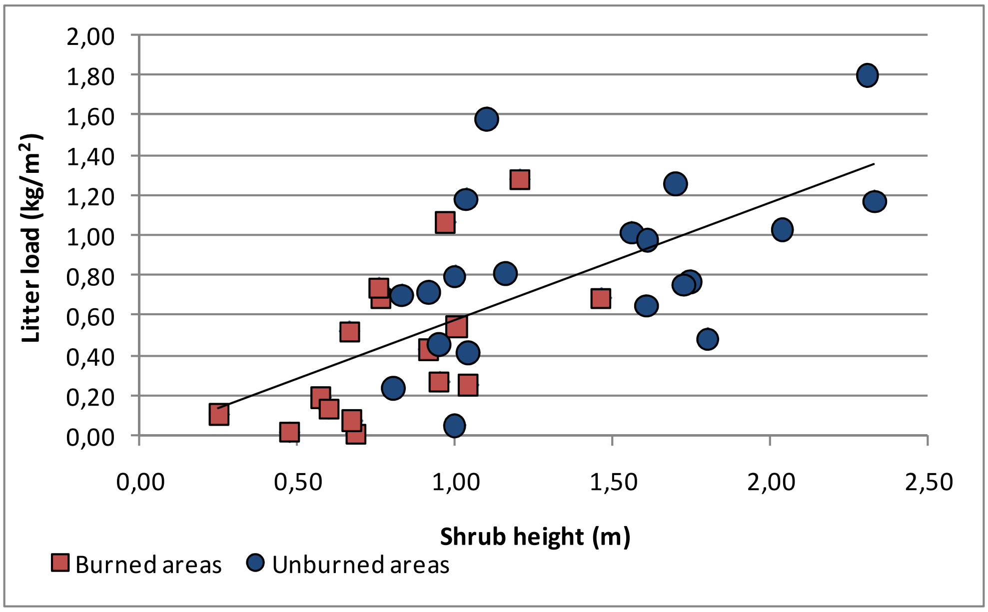


Figure 79. Litter load as a function of shrub height (m) for the total dataset

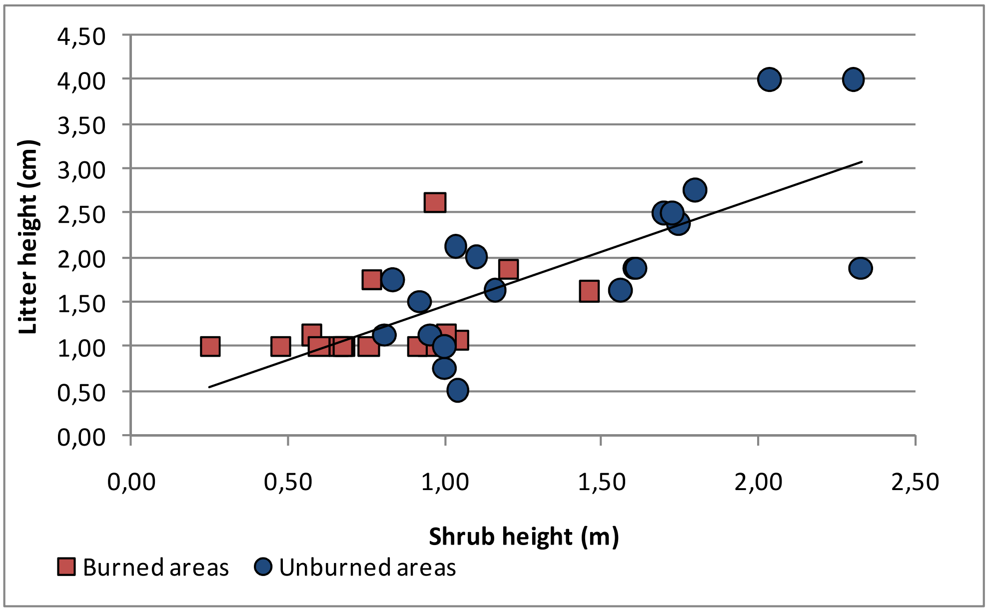


Figure 80. Litter height (cm) as a function of shrub height (m) for the total dataset

Table 49. Coefficient and power function regression equations between litter load and shrub height (equation a) and litter height and shrub height (equations b and c)

Dependent variables	Model form	Constant and coefficients		df	R^2	MS	F	*p*
a)Total Litter load	y= b(*s_height*) - k	k: 0.006	SE: 0.143	1, 34	0.437	0,118	26.360	0,0001
		b: 0.587	SE: 0.114					
b)Total Litter height	y= b(*s_height*) + k	k: 0.245	SE: 0.227	1, 14	0.570	0,298	45.005	0,0001
		b: 1,219	SE: 0.182					
c)Litter height in unburned plots	y= b(*s_height*) -k	k: 1.417	SE: 0.295	1, 18	0,561	0,393	23.020	0,0001
		b: 0.058	SE: 0.440					

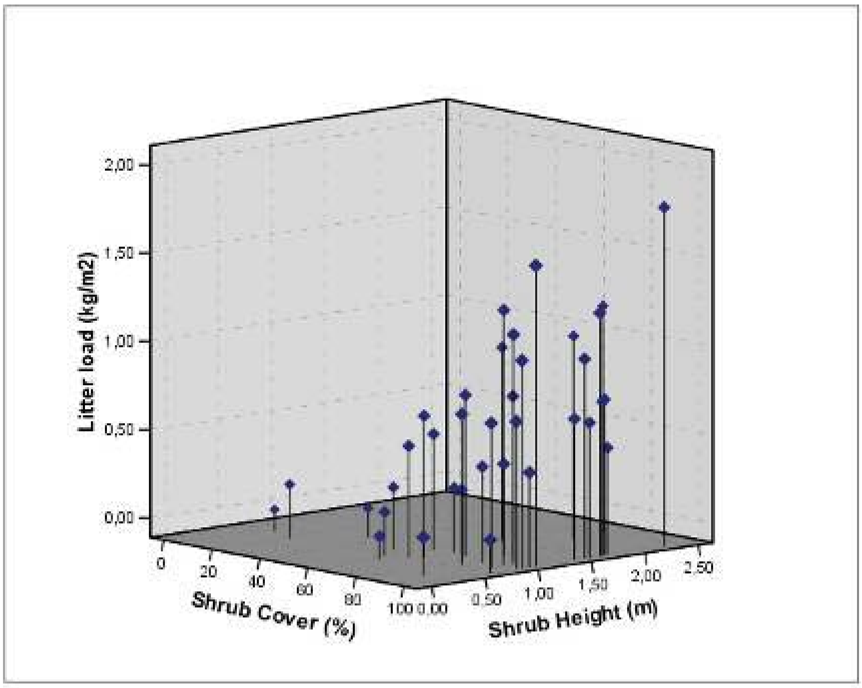


Figure 81. Relation among litter loads, shrub height and cover

8.4. Maquis fuel type

In order to define the main maquis fuel type that mainly could express the variability surveyed in the field, a cluster analysis using Ward's was performed with the row data collected in the field. Considering the dendrogram obtained through the analysis, fundamentally four large clusters were recognizable (Figure 82).

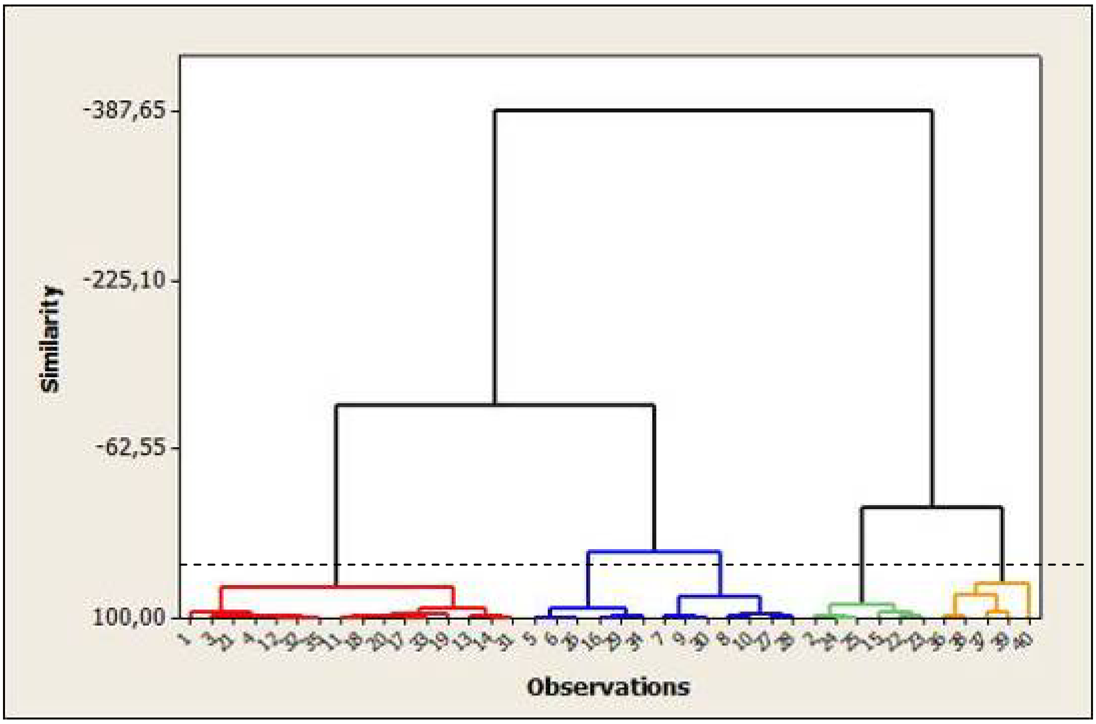


Figure 82. Cluster hierarchical analysis performed using Ward's methods

The largest cluster (in red) was constituted essentially by plots of area LC3, area PP, and area MD2, characterized by a medium height and close cover (Table 50). The second group (in blue) comprised almost all plots of the areas that have been recently burned, and it was distinguished from the others by the low high and a medium-open cover. The third cluster (in green) was composed of areas with close cover and average height of 1.60 m. The fourth group (in orange) was characterized by a dense cover, and an average height of 2 meters. Moreover, inside the second group two more sub-groups were present, the first characterized by the most recent passage of the fire (MD1 and LC2) and the second by plots with low high and medium cover. The average value of height and cover of all plots grouped in these clusters were then considered, and classified according with an adaptation of Prometheus classification system (1999), developed for obtaining a standardization system of maquis properties classification: in this way the groups indentified in the cluster analysis were classified in four fuel types of shrub (Table 51). The first group corresponded to medium high and close maquis, the second to medium maquis (in which it was possible to recognize low and open maquis), the third and the fourth were characterized by high and close maquis.

With the aim to consider different typologies of fuel that mainly could express the variability surveyed in the field, also based on the knowledge of the territory, the cluster 3 and 4 were aggregated, and the cluster 2 was decomposed in group 2a and 2b. Therefore the shrubland fuel types evidenced in this manner reflected differences in the total amount and class distribution of the fuel load and in the vegetation structure (cover and height) (Table 52).

Table 50. Main characteristics of the clusters evidenced by cluster analysis

Cluster	*Height (m)*	*Cover %*
1	1.01	85.18
2	0.60	53.73
2a	*0.78*	*72.66*
2b	*0.44*	*37.50*
3	1.63	100.00
4	2.02	81.94

Table 51. Definition of the fuel type evidenced by cluster analysis

Cluster	*Fuel Type*
1	Medium height and close maquis
2	Medium maquis
2a	*Medium maquis*
2b	*Low and open maquis*
3	High and close maquis
4	High and close maquis

Table 52. Maquis fuel type considered in this study. S.d. standard deviation. Different letters indicate significant differences ($p < 0.05$) with ANOVA and LSD *post hoc* test

Fuel type	*Average height (m) (s.d.)*	*Cover (%)*	*Litter load (Mg ha⁻¹)*	*Shrubs fuel load by category (Mg ha⁻¹)* *Live* *1 hr*	*Live 10 hr*	*Live 100 hr*	*Dead 1 hr*	*Dead 10 hr*	*Dead 100 hr*	*Total shrub fuel load (Mg ha⁻¹)*
Low and open maquis	0.44 [a] (0.25)	37.50 [a]	1.38 [a]	2.05 [a] (42.62%)	0.40 (8.32%)	0.04 (0.83%)	0.82 (17.05%)	1.42 (29.52%)	0.07 (1.46%)	4.81 [a]
Medium maquis	0.78 [b] (0.19)	72.66 [b]	3.48 [ab]	7.89 [ab] (35.56%)	2.97 (13.38%)	1.25 (5.63%)	2.02 (9.10%)	7.50 (33.80%)	0.57 (2.57%)	22.19 [ab]
Medium height and close maquis	1.00 [c] (0.12)	85.18 [b]	6.42 [b]	10.48[b] (38.44%)	5.88 (21.57%)	2.17 (7.96)	3.25 (11.92%)	2.41 (8.84%)	0.57 (2.09%)	27.26 [b]
High and close maquis	1.81 [d] (0.29)	91.79 [b]	9.67 [c]	12.75[c] (31.35%)	15.95 (39.22%)	4.95 (12.17%)	2.69 (6.61%)	4.23 (10.40%)	0.04 (0.11%)	40.67 [c]

Fuel type “low and open maquis” (Figure 83) included young maquis with fuel complex structure characterized by low height and open cover, up to 40%, with a high proportion of live fine load (foliage and twig smaller than 0.6 cm); the fine deal fuel component contributed only for the 16% at the total fuel load, due to its youth. In Fuel type “medium maquis” (Figure 84), the fuel complex structure was taller than the first type, characterized by a less live fine load (36%). The third fuel type incorporated a maquis of medium height and dense cover (Figure 85), with live fine load contribution comparable to the second fuel type, but there was substantial live fuel load distributed to the other classes. Finally, the fuel type “High and close maquis” (Figure 86) showed a mature and high maquis, with average height of 1.81 meters, and a distribution of the fuel load in the classes with diameter comprised between 0.6 and 0.25 cm, both live than dead, due probably to heavier branching development, as the age of the plant increases.

Statistical analysis conducted with ANOVA and LSD *post hoc* test showed that the four fuel types were statistically different. In particular, the vegetation heights of all fuel types was found to be statistically different at $p < 0.05$, whereas for litter load, live fine material and total loads the “medium maquis” fuel type was not different from “low and open maquis” and “medium height and close maquis”.

Figure 83. Low and open maquis

Figure 84. Medium maquis

Figure 85. Medium height and close maquis

Figure 86. High and close maquis

8.5. Custom fuel model development

In order to develop the fuel models describing the Mediterranean maquis, the row data collected in the field work and grouped in four fuel type, were generalized adapting the methodology developed and explained in BEHAVE-Subsystem FUEL (Burgan and Rothermel, 1984), and therefore the program BehavePlus 3.0 (Andrews et al., 2005) has been used to perform potential fire behaviour of the four models.

BehavePlus 3.0 needed in principal five input parameters (biomass live and dead, surface-to-volume-ratio, depth of fuel layer, moisture of extinction). In Table 53 are summarized the input used to develop the fuel models. BehavePlus permitted to evaluate the desiderated range of potential fire behavior, using as input data the fuel values of each model. In this study, two burning conditions combining two moisture scenarios and three wind speeds were used.

Table 53. Input used during the development of custom fuel models (CM)

Custom model	*CM1*	*CM2*	*CM3*	*CM4*
Fuel type	*Young low and open maquis*	*Medium maquis*	*Medium height and close maquis*	*High and close maquis*
Total Fuel Load (Mg ha^{-1})	**8.77**	**23.39**	**25.38**	**31.13**
Dead fuel load	*6.39*	*15.20*	*14.54*	*18.18*
Dead 1 h	3.89	5.68	10.07	12.81
Dead 10 h	2.43	8.95	3.85	5.33
Dead 100 h	0.07	0.57	0.62	0.04
Live Fuel load	*2.38*	*8.19*	*10.84*	*12.95*
Live woody	2.05	7.89	10.48	12.76
L ive herbaceous	0.33	0.30	0.36	0.19
SAV (m^{-1})				
σ dead	1964	2427	2290	2906
σ live	4464	5609	5847	5578
Fuel Complex depth δ (m)	0.48	0.7	0.84	1.63
Fuel Heat Content (kJ kg^{-1})				
Dead	18620	18620	18620	18620
Live	18620	18620	18620	18620
Fuel moisture of extinction (%)	25	25	25	25

Table 54 showed the predicted fire behaviour results. The values accounted were the ranges (upper and lower limit) due to the different wind speeds. All fire behaviour predictions referred to flat terrain.

Table 54. Potential fire behaviour in dry and moist condition scenarios for the four custom fuel models

Fuel model	*Rate of Spread* (*m min⁻¹*)	*Heat per Unit Area* (*kJ m⁻²*)	*Fireline Intensity* (*kW m⁻¹*)	*Flame Length* (*m*)
		dryness condition		
CM1	0.3 -14.7	10658	62 - 2619	0.5 – 2.9
CM2	0.5 – 17.2	23497	201 - 6719	0.9 – 4.5
CM3	0.8 – 28.4	32371	437 - 15306	1.3 – 6.5
CM4	1.4 – 57.7	38699	887 - 37200	1.8 – 9.8
		moist condition		
CM1	0.2 – 8.1	9061	29 -1224	0.4 – 2.0
CM2	0.3 – 8.9	18095	80 – 2684	0.6 – 2.9
CM3	0.4 – 14.6	24663	171 – 6012	0.8 – 4.2
CM4	0.8 – 33.7	32861	441 - 18474	1.3 – 7.1

As expected, CM3 and CM4 had the most severe fire potential due to the heavier fuel loads, but they differentiated notably in the order of magnitude; whereas, the potential rate of spread of CM1 and CM2 was almost similar (Figure 87). This was due probably to the fuel load composition of CM2: even if the component dead had a very high load of fine fuel less than 2.5 cm of diameter, the rate of spread was restrained by the live fine fuel component, accounting the 33% of the total fuel load in the model. Similarly, the CM1 and CM2 resulted in less fireline intensity compared to fuel models CM3 and CM4, whereas the models were well distinguished taking in account the potential flame length.

Regarding the predicted fire behave in moisture scenario simulating a humid condition (Figure 88), shrubland fuel models CM3 and CM4 showed the most severe fire potential due to the heavier fuel loads, but they differentiated because the range was not broad as during the simulations setting dry conditions.

The potential rate of spread of CM1 and CM2 was similar. Similarly, the fuel models CM1 and CM2 trends in fireline intensity were similar to the dry conditions.

The fuel values represented by the models fell well within the range reported for Mediterranean vegetation types in other parts of the world. Table 55 showed the comparison among the custom fuel models developed in this study and the standard fuel models for use with Rothermel's (1972) surface fire spread model, and a simulation setting dry conditions was performed with BehavePlus 3.0 (Figure 89 and Figure 90). Predicted spread rate were compared over a range of 15 km ha^{-1} windspeed. The data of CM4, which correspond to a mature maquis, high and close, were similar to those of fuel model 4 of Anderson (1982). Examples fitting this fuel model were stands of mature shrubs, 2 m or more tall, "*such as California mixed chaparral, the high pocosin along the east coast, the pine barrens of New Jersey, or the closed jack pine stands of the north-central States*" (Anderson, 1982). The fuel model 4 total fuel load was 35.93 Mg ha^{-1}, whereas for CM4 it was 31.13 Mg ha^{-1}. Also, the data of the CM4 single fuel components were similar to those of fuel model 4, in particular the dead 1hr and live 1 hr components. Also the sh7 fuel model (Scott and Burgan, 2005), described having *"...very heavy shrub load, depth 1.30-2 m*", had a similar load (32.28 Mg ha^{-1}) that can potentially carry the fire, but in this case the dead 1 hr and 10 hr load were opposite to those evidenced in CM4. The litter load, in effect, was included as dead 10 hr fuel rather than as 1 hr fuels as might be done based on the SAV of the individual litter particles (Scott and Hungerford, 1997). Moreover, the parameters of the custom fuel model here developed were in agreement with several studies conducted to determine fuel models of Mediterranean basin vegetation. Dimitrakopoulos (2002) reported two fuel models relative to evergreen-sclerophyllous shrublands, similar in fuel load to CM2 and CM3, with similar potential fire behaviour in moist conditions. 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.

The data of CM1, representing low and open maquis, were similar to those of fuel model 5 of Anderson (1982), described as light surface fuel loads, young short shrubs with little dead material, covering almost totally the area, such as

"...laurel, vine maple, alder, or even chaparral, manzanita, or chamise" (Anderson, 1982).

Nevertheless the similarity, the FM4 predicted faster spread rates that CM4 at the fuel moisture encountered in maquis in dryness conditions (Figure 89), whereas the standard fuel model sh7 predicted lower spread rates, despite higher fuel load. The packing ratio was lower than the FM4 and CM4, and this should lead to higher spread rates, especially in windy conditions, but the higher dead 10 hr component with relatively low SAV restrained the rate of spread, therefore comparable to those of CM3. In the same way, despite the similarity between CM1 and FM5, the low packing ratio and the high SAV brought near the rate of spread of FM5 to CM3, whereas the fireline intensity was similar to CM1, because the slightly higher load.

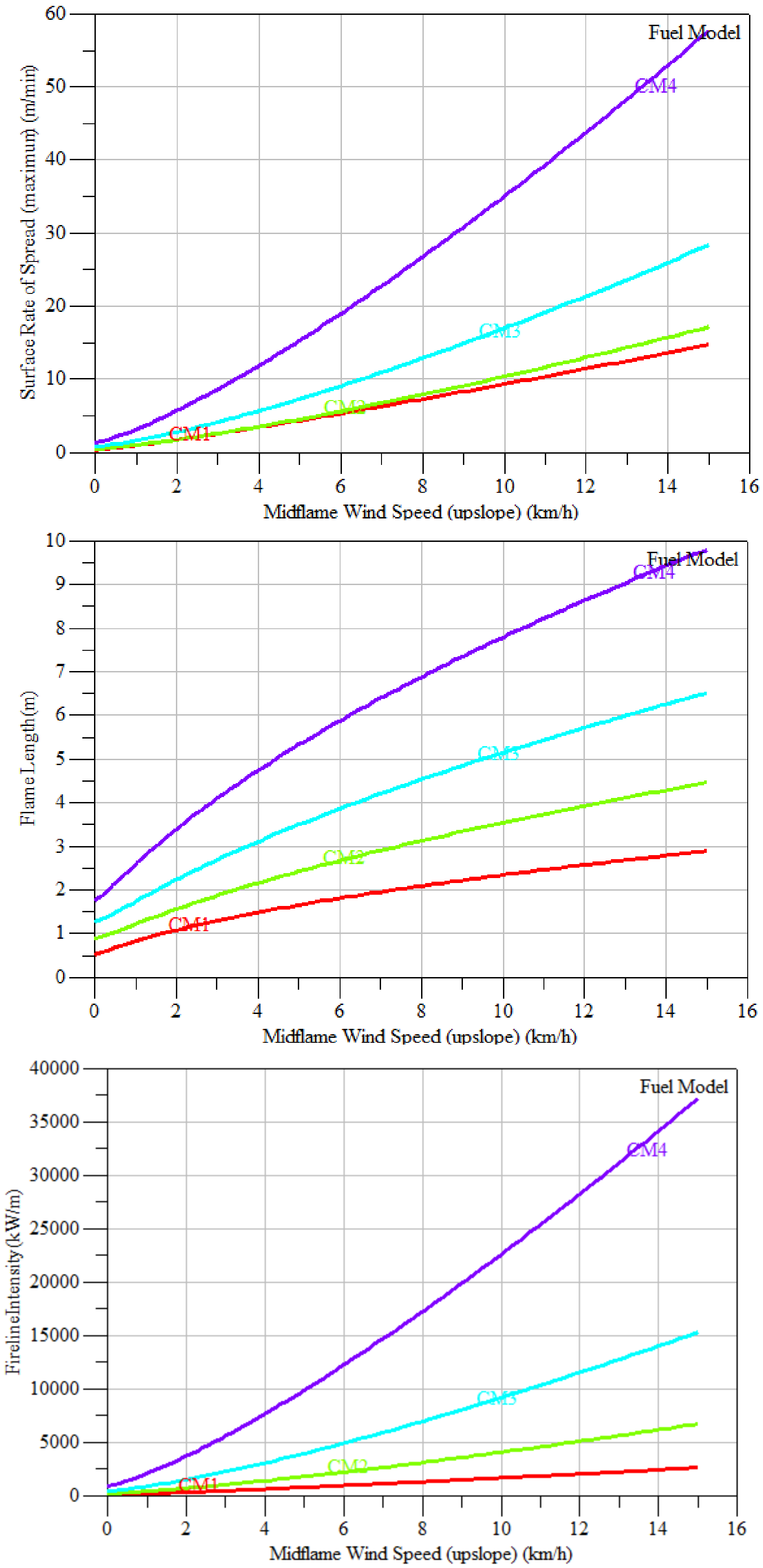


Figure 87. Potential fire behaviour for the four custom fuel models in dry conditions

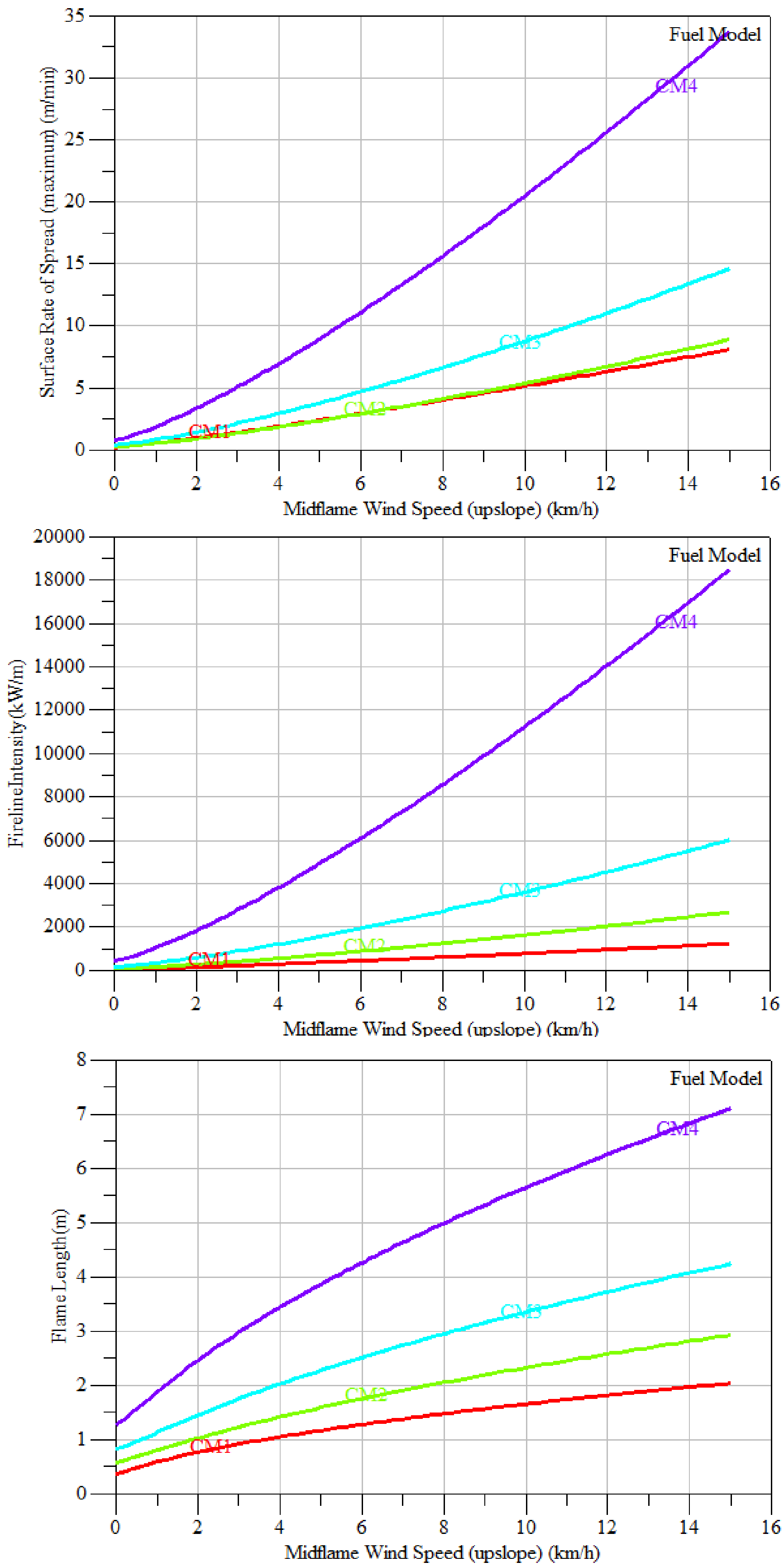


Figure 88. Potential fire behaviour for the four custom fuel models in moist conditions

Table 55. Comparison among the Custom fuel models and the standard fuel models

Fuel model	*CM1*	*CM2*	*CM3*	*CM4*	*4 (Anderson, 1982)*	*5 (Anderson, 1982)*	*sh2 (Scott and Burgan, 2005)*	*sh5 (Scott and Burgan, 2005)*	*sh7 (Scott and Burgan, 2005)*
Description	*Low and open maquis*	*Medium maquis*	*Medium height and close maquis*	*High and close maquis*	*High and close mature shrub*	*Low and dense shrub*	*Moderate fuel load, low shrub*	*Heavy fuel load, high shrub*	*Very heavy fuel, load high shrub*
Total Fuel Load (Mg ha^{-1})	8.77	23.39	25.38	31.13	35.93	7.86	18.72	19.28	32.28
Dead fuel load	*6.39*	*15.2*	*14.54*	*18.18*	*24.7*	*3.37*	*10.09*	*12.78*	*24.66*
Dead 1 h	3.89	5.68	10.07	12.81	11.23	2.25	3.03	8.07	7.85
Dead 10 h	2.43	8.95	3.85	5.33	8.99	1.12	5.38	4.71	11.88
Dead 100 h	0.07	0.57	0.62	0.04	4.48	0	1.68	0	4.93
Live Fuel load	*2.38*	*8.19*	*10.84*	*12.95*	*11.23*	*4.49*	*8.63*	*6.5*	*7.62*
Live woody	2.05	7.89	10.48	12.76	11.23	4.49	8.63	6.5	7.62
Live herbaceous	0.33	0.3	0.36	0.19	0	0	0	0	0
SAV (m^{-1})									
σ dead	1964	2427	2290	2906	6562	6562	6562	2461	2461
σ live	4464	5609	5847	5578	4921	4921	5249	5249	5249
Fuel Complex depth δ (m)	0.48	0.70	0.84	1.63	1.82	0.61	0.33	1.83	1.83
Fuel Heat Content (kJ kg^{-1})									
Dead	18620	18620	18620	18620	18620	18622	18622	18622	18622
Live	18620	18620	18620	18620	18620	18622	18622	18622	18622
Fuel moisture of extinction (%)	25	25	25	25	20	20	15	25	25
Packing ratio	0.0036	0.0065	0.0059	0.0059	0.0038	0.0025	0.012	0.0021	0.0034

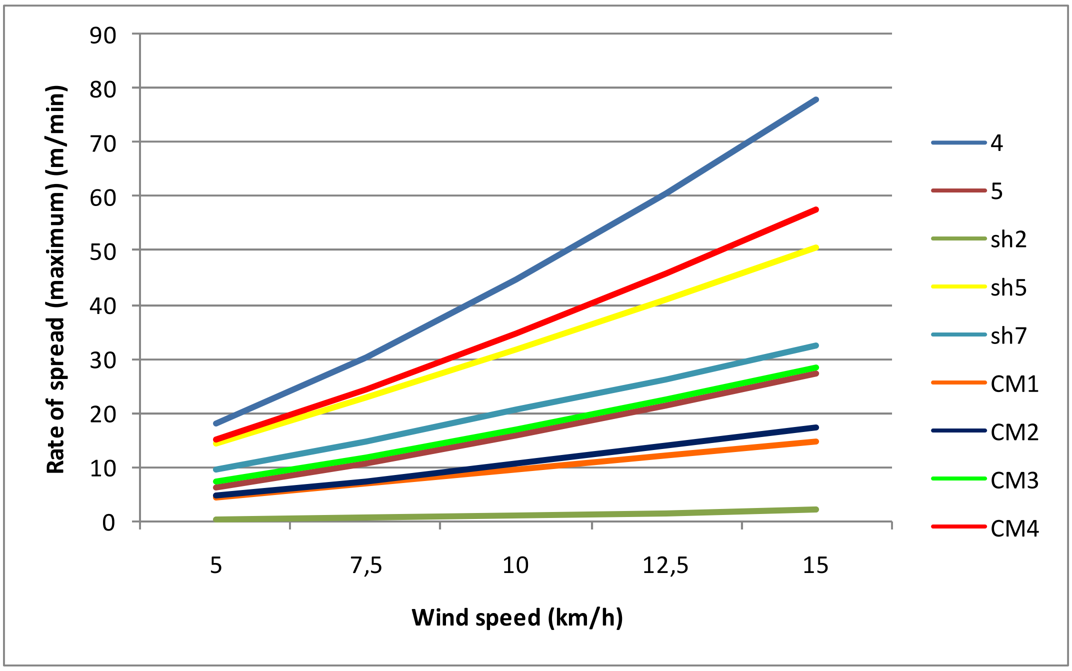


Figure 89. Potential rate of spread (m min^{-1}) for the four custom fuel models and several standard fuel models in dry conditions

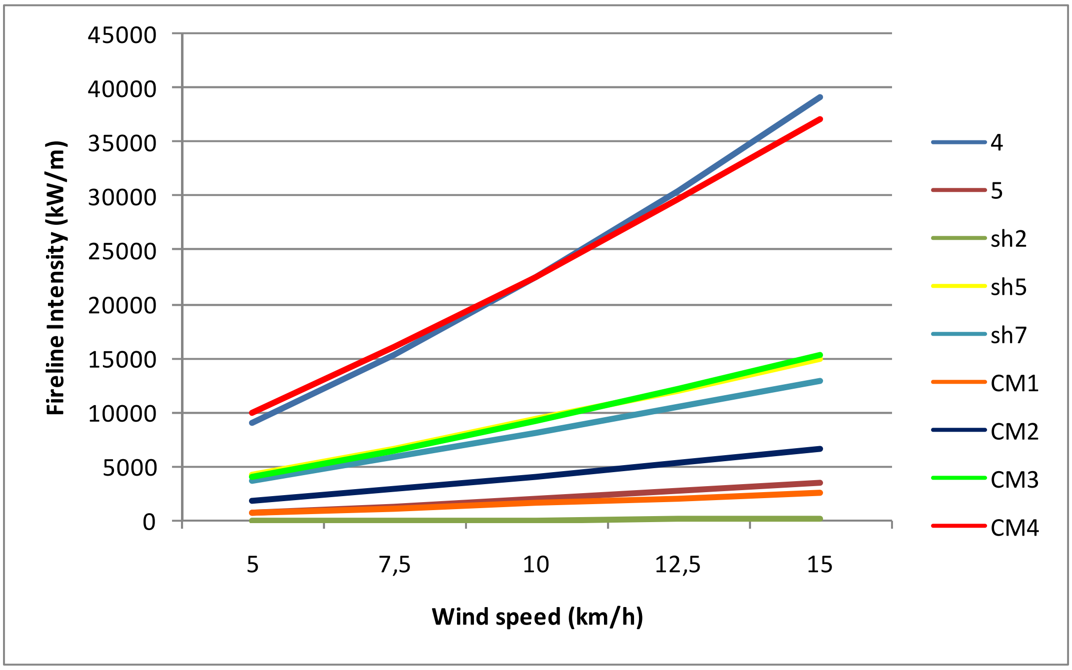


Figure 90. Potential fire line intensity (kW m^{-1}) for the four custom fuel models and several standard fuel models in dry conditions

8.6. Fuel type mapping

Significant patches corresponding to areas representative of the four fuel type classes, recognized in this study on the basis of field work and satellite image analysis, were carefully identified over the IKONOS image, with the addition of the classes concerning areas having "No Fuel", "Agriculture and pasture", and "Woody". The "No Fuel" class comprised all areas presenting roads, urban areas soils with no vegetation cover, emerging rocks, woody cultivations, arboreal cultivations (mainly orchards and olive-groves) and irrigated fields, water bodies. The "Agriculture and pasture" class comprised areas having crops, grasslands, pastures, meadows, herbaceous vegetation growing in areas no longer agriculturally used and uncultivated soils. The "Woody" class comprised mainly broad-leaved mixed forest.

The IKONOS image, "trained" with the training sites, was used to map fuel types, using the direct mapping approach (Keane et al., 2001). The results of the supervised classification are shown in Table 56 and Figure 91. Accuracy assessment of the vegetation classification was accomplished through the use of error matrices detailing producer's and user's accuracies, overall accuracy and overall Kappa statistic. Values corresponding to "producer's accuracy" indicated the probability of a reference sample being correctly classified; "user's accuracy" was indicative of the probability that a sample classified on the map actually represented that category on the ground (Congalton, 2001).

The supervised classification showed a high fuel type overall accuracy (72.73%), with a Kappa coefficient was 0.67, whereas considering only the overall accuracy for maquis fuel type, it reached up to 68.85%.

According to the error assessment matrix (Table 56), the main sources of error among all classes came from the "Woody" class, with a user's accuracy of 37.50%. This class was underestimated and some "Woody" pixels were misclassified as "High and close maquis". These two classes presented remarkable "exchange" of pixel because the classifier "moves" 20% of the pixels attributed to "High and close maquis" toward "Woody" and 12% to "Woody" toward "High and close maquis". The mistake was above all attributed to the difficulty to distinguish spectrally the two classes, which are very like as regards the vegetational characteristics (broad leaved and sclerophyllous), being different above all on the structural plan.

Among the maquis fuel type classes, the main source of error was "Low and open maquis", with a user's accuracy of 58.33%. Also this class was underestimated, and some pixels were misclassified as "Agriculture and pasture", the classifier "moving" 16% of the pixels. The mistake was above all attributed to the ability of the classifier to distinguish very well bare soil and herbaceous components, but those were also component of the "low and open maquis" (Figure 92, left).

The overall accuracy results presented by Lasaponara and Lanorte (2007b) using Quickbird satellite images, comparable to IKONOS, achieved 75%. The worst producer's accuracy they achieved was for fuel type 3 (Mediterranean scrubs, garigues and shrubby prairies) and 4 (Mediterranean scrubs) was 36.08 and 67.67% respectively, whereas only fuel type 3 showed a medium user accuracy (55.28%). Arroyo and collaborators (2006) reported overall accuracies of 75% and 0.69 of kappa value when evaluating the effectiveness of using a pixel-based classification of Quickbird satellite image for mapping cover types. They reported that the main sources of error came from the "high shrub" class, with a users accuracy of 50%. The "medium shrub" class showed a producer accuracy of 67%, similarly to the "short shrub", whereas their user's accuracy was higher (88 and 80% respectively).

A behaviour noticed in this work, but reported also by other authors (Blaschke and Strobl, 2001; Sawaya et al., 2003; van der Sande et al., 2003) was that the high spatial resolution increased the spectral within-field variability. Thus the supervised classification was hampered by this higher variability.

Table 56. Quantitative Accuracy assessment (*) (**)

	Reference data								
	Agriculture and pasture	High and close maquis	Medium height and close maquis	Medium maquis	Low and open maquis	Woody	No fuel	Sum	User's Accuracy
Agriculture and pasture	36	0	1	1	2	0	0	40	90.00%
High and close maquis	0	14	0	1	0	4	0	19	73.68%
Medium height and close maquis	1	1	15	0	1	2	1	21	71.43%
Medium maquis	1	1	4	6	1	2	0	15	40.00%
Low and open maquis	2	0	0	1	7	2	1	13	53.85%
Woody	0	2	0	1	1	6	0	10	60.00%
No fuel	1	1	0	0	0	0	12	14	85.71%
Sum	41	19	20	10	12	16	14	132	
Producer's Accuracy	87.80%	73.68%	75.00%	60.00%	58.33%	37.50%	85.71%		

*Overall classification accuracy is 72.73%

**Overall Kappa accuracy is 0.67

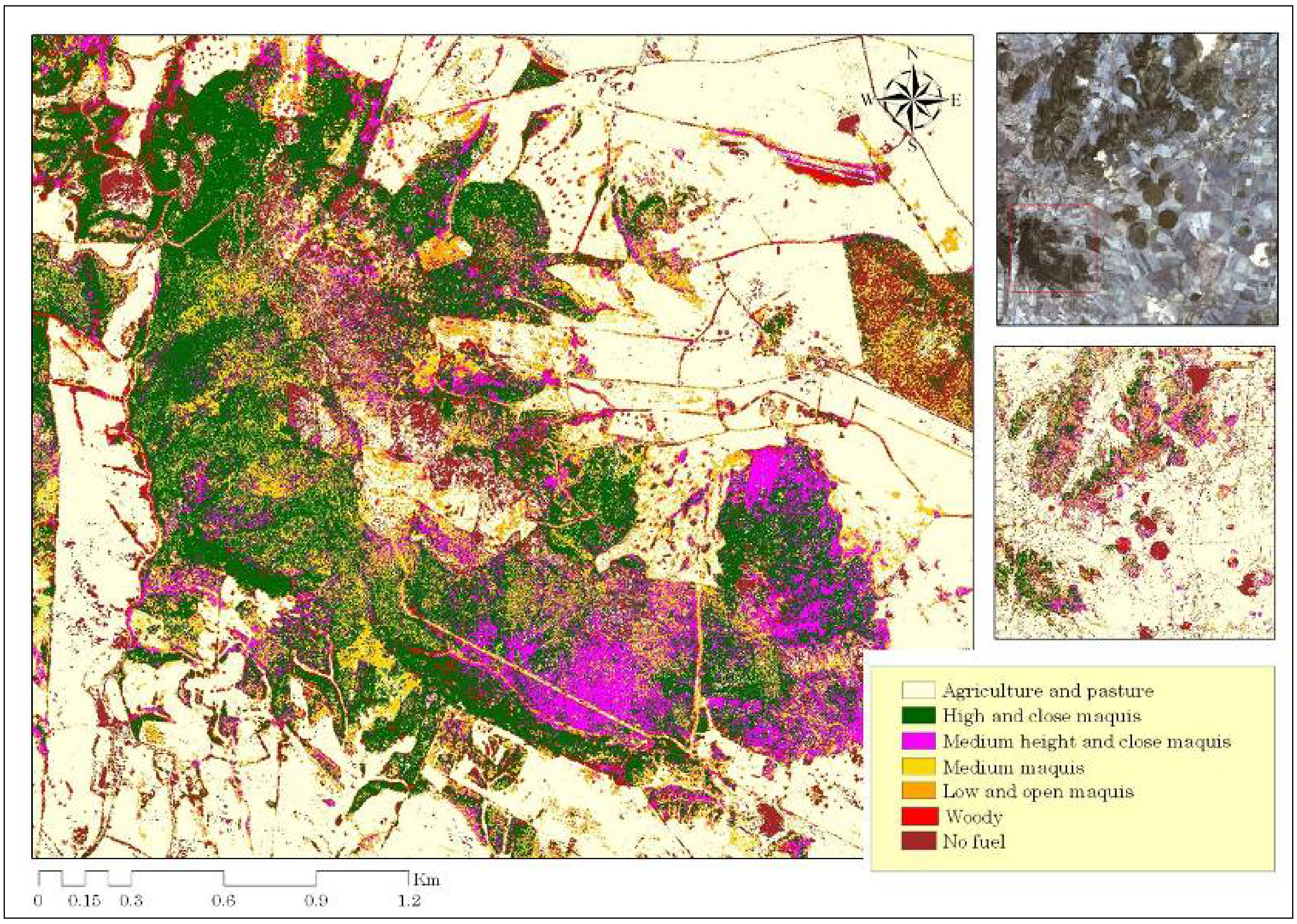


Figure 91. Detail of the IKONOS Supervised Classification; IKONOS satellite image (above, right) showing the map detail within a red rectangle; whole IKONOS Supervised Classification (down, right)

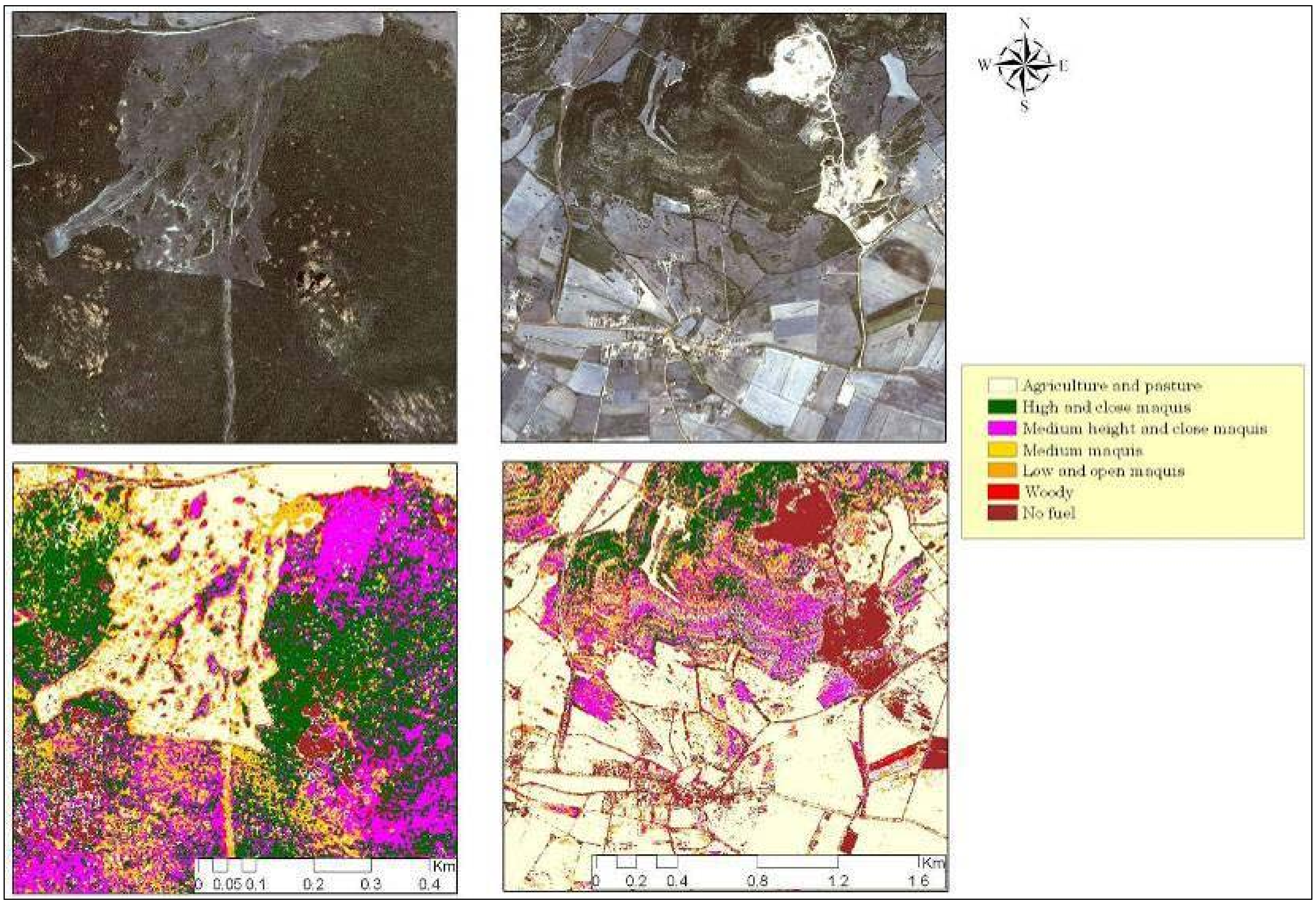


Figure 92. Details of the IKONOS Supervised Classification

Other fuel mapping studies that used coarse scale satellite imagery, and a more complicated biophysical modeling approach, showed overall accuracies similar to those obtained in this thesis. Using Landsat TM imagery, Keane et al. (2000) reported an overall accuracy of 36% and an overall kappa value of 45% for their forest type layer, which was analogous to fuel type. Falkowski et al. (2005), using ASTER imagery and biophysical mapping approach (Keane et al. 2001), achieved an overall accuracy of 72% and a kappa value of 63% for their cover type map, showing a suitable mapping method when using ASTER data. Riano et al. (2002) reported overall accuracies of 58% to 67% and kappa values of 51% and 61% when evaluating the effectiveness of using a single date of Landsat TM imagery compared to using an image comprised of multiple dates of Landsat TM imagery for mapping fuel types.

The fuel type map obtained with the methodology described above had a very fine resolution (0.80 m pixel). With the aim of better understand how fine resolution fuel maps affected the fire spread predictions, the map fuel type was re-sampled using Nearest Neighbour classifier algorithm, with a resolution of 5, 10, 15 m. Custom fuel models and fuel models were thus assigned as follows: CM1 to open and low maquis, CM2 to medium maquis, CM3 to medium height and close maquis, CM4 to high and close maquis, FM1 (Anderson, 1982) to "Agriculture and pasture", FM99 (Scott and Burgan, 2005) to the areas classified as "No fuel" and "Woody". The re-sampling and fuel model assignments results are shown in Figure 93 and Figure 94.

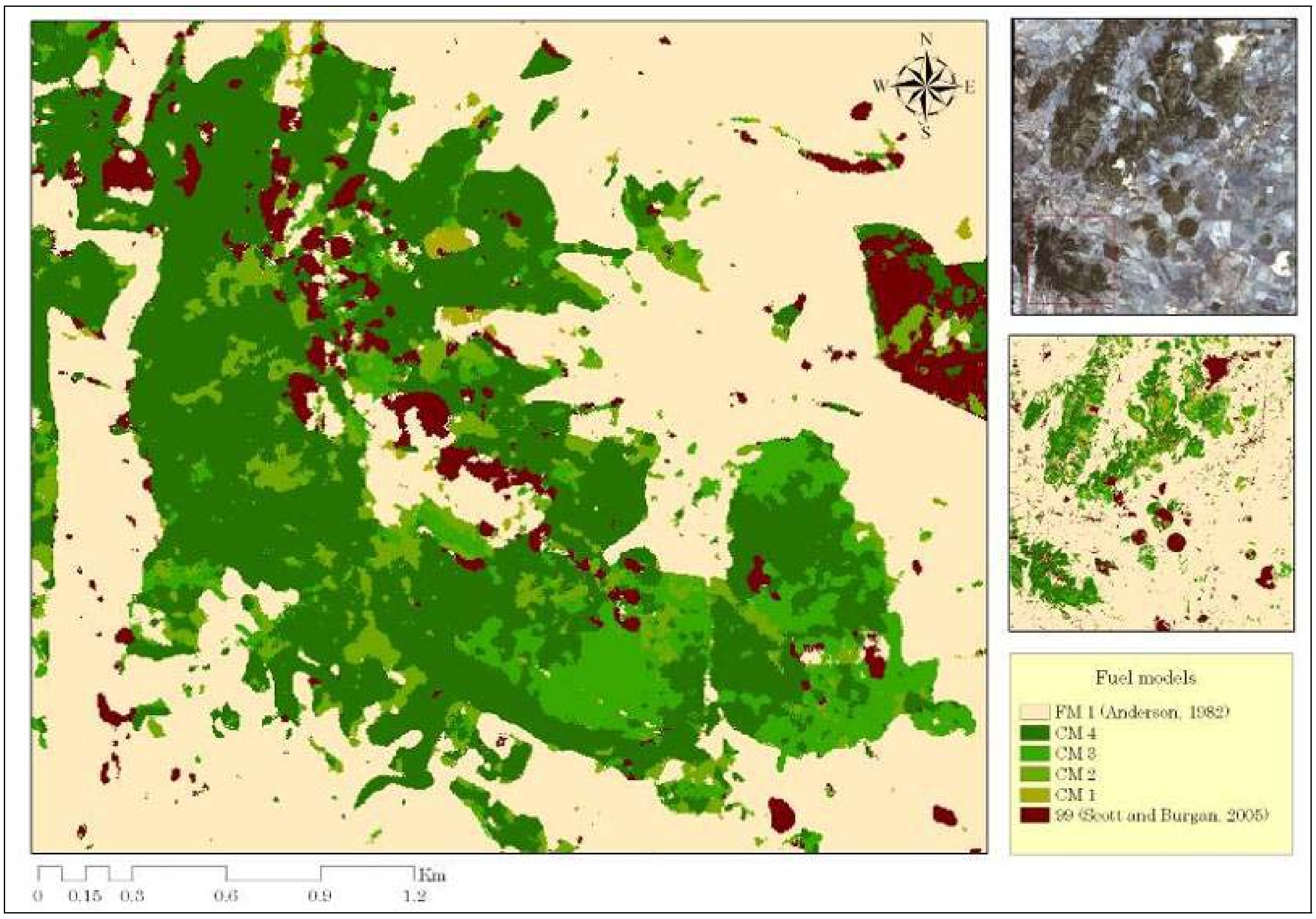


Figure 93. Particular of fuel map resampled at 5 meters (left), IKONOS satellite image (above, right) showing the map detail within a red rectangle; whole fuel map resampled (down, right)

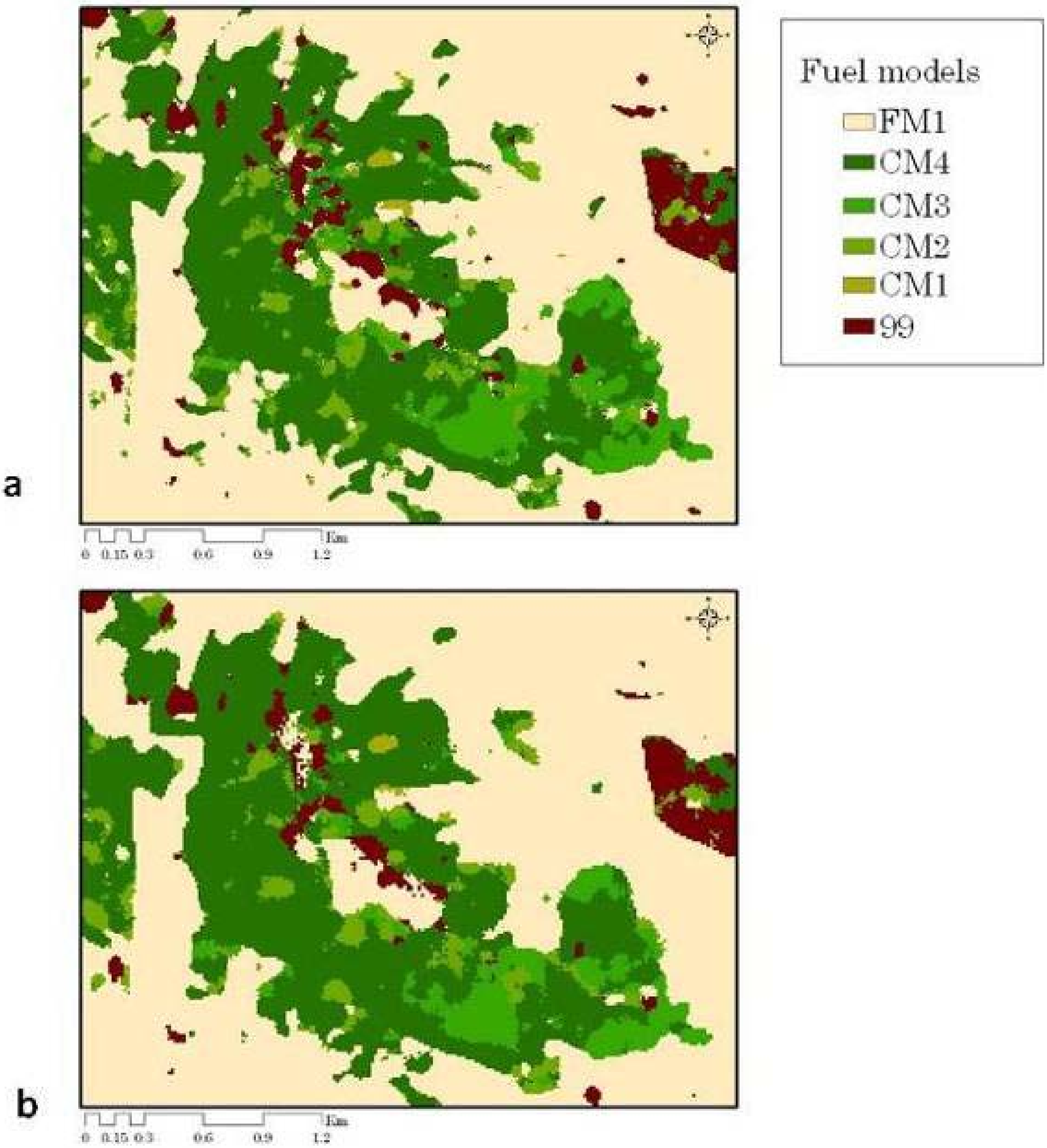


Figure 94. Particular of fuel maps resampled at 10 (a) and 15 meters (b)

8.7. Sensitivity analysis of FARSITE

The fuel model maps thus obtained were imported in FARSITE (Finney, 2004). The results from these simulations would show if changing the fuel map resolution would produce different results in the simulation. A total of six simulations were run from an ignition points using FARSITE. The inputs layers for the study areas were held constant in all the simulations except the fuel map layers. The general description of the simulation performances for the final fire perimeters and average rate of spread are reported in Table 57.

Table 57. Simulation performances for the final fire perimeters and average rate of spread

Resolution map	5 km h^{-1}		10 km h^{-1}	
	Area (ha)	ROS (medium) (m min^{-1})	Area (ha)	ROS (medium) (m min^{-1})
5	73.6	4.77	121.8	7.89
10	94.7	6.20	177.3	9.56
15	111.00	6.31	203.4	9.95

Table 58. Difference (%) from reference (5 m map)

Resolution map	5 km h^{-1}		10 km h^{-1}	
	Area	ROS (medium)	Area	ROS (medium)
10	+ 28.67	+ 29.98	+ 45.56	+ 21.16
15	+ 50.81	+ 32.28	+ 66.99	+ 26.11

Maps of simulated fire behaviour and spread, using wind speed constant at 5 km h^{-1}, were shown in Figure 95. In these simulations, the fire stopped at the northern flank due to the presence of a down slope area in all three fuel maps, but it was interesting to observe that in the fuel map at 5 m the fire extinguished at the top of the hill due to several areas of no fuel and fuel model CM7, as well as FM1 areas (Figure 95, a). The first front of the fire simulated with fuel map at 10 stopped almost at the same point, but it surrounded these areas, continuing its spread in two fronts (Figure 95, b and c). In the map 15 m map, where the no fuel areas had small dimensions, it was observed an uniform advancement of the fire front, and only a slowing down in those areas presenting custom fuel model 17. The sensitivity analysis showed an increase of about 30% in burned area in fuel map re-sampled at 10 and about 51% in map resample at15 m compared to the fuel map at 5 m, using a constant winds peed of 5 km h^{-1} (Table 58).

The ROS gave general information on the effect of fuel and environmental conditions on fire behaviour. With winds peed of 5 km h^{-1} predicted ROS ranged from 0 to 16 m min^{-1} using the 5 m and 15 m re-sampled fuel maps (Figure 95, a and c), from 0 to 18 m min^{-1} using the 10 (Figure 95, b). Considering the ROS medium the differences between the different fuel maps was small: the estimated average rate of spread was 4.77 m min^{-1} for map resampled at 5 m, 6.20 m min^{-1} for 10 m, and 6.31 m min^{-1} for map resampled at 15 m (Table 57). Areas towards the central part of the burned area experienced higher rates of spread (ranging from a minimum of 7 to a maximum of 18 m min^{-1}) than other areas in all three fuel maps, due to the presence of the custom fuel model CM4, representing high and close maquis. The area where FM1 was assigned showed the lowest rate of spread, usually from 0 to 2 m min^{-1}. The sensitivity analysis showed an increase of about 30% in ROS in fuel maps resampled at 10 and 32% in 15 m compared to the ROS of fuel map at 5 m (Table 58).

Map of simulated fire behavior and spread, using wind speed constant at 10 km h^{-1}, are shown in Figure 96. In these simulations, fire split at the top of the hill in two fronts also using the fuel map at 5 m: this area was patchy, with the presence of many “islands” of no fuel and fuel model CM2, as well as FM1 areas. With fuel map at 10 and 15 m fire propagated more in the two fronts, and the differences among the use of the three fuel maps at different scales was well evident: the simulated fire spread carried on all those areas that in the fuel map at 5 m were too fragmented to sustain the fire. The sensitivity analysis showed an increase of about 45% in burned area (ha) in fuel maps re-sampled at 10 and 66% in 15 m fuel map compared to the fuel map at 5 m (Table 58).

With wind speed at 10 km h^{-1} the first set of simulations predicted ROS ranging from 0 to 30 m min^{-1} using the 5 m re-sampled fuel map (Figure 96, a); from 0 to 26 m min^{-1} using the 10 m (Figure 96, b)and from 0 to 22 m min^{-1} using the 15 m fuel maps (Figure 96, c). Considering the ROS medium, the differences between the different fuel maps were small: the estimated average rate of spread was 7.89 m min^{-1} for map re-sampled at 5 m, 9.56 m min^{-1} for map re-sampled at 10 m, and 9.95 m min^{-1} for map re-sampled at 15 m (Table 57). Again, the areas experiencing higher rates of spread (ranging from a minimum of 9 to a maximum of 30 m min^{-1}) than other areas in all three fuel maps were those with custom fuel model CM4, representing high and close maquis. The areas where FM1 was assigned showed the lowest rate of spread, usually from 0 to 3 m min^{-1}. The sensitivity analysis showed an increase of about 21.16% in ROS in fuel maps resampled at 10 and 26.11% in 15 m compared to the ROS of fuel map at 5 m (Table 58).

In order to obtain realistic simulations of spatial fire growth and behaviour, fuel maps must be developed at *fine resolutions* (Finney, 2005). In this study, the simulations using the three fuel map created a baseline to understand how fire would react in Mediterranean areas using fuel map with different fine resolution scale. The results among the fuel maps showed that the maximum and average rate of spread and the area burned changed due to scale resolution, that is, FARSITE was sensitive to the change in fuel map resolution. The results for rate of spread increased especially for medium intensity wind speed from 5 m map to 15 m. The outputs maps showed also that areas to which custom fuel model CM4 was assigned had greater rates of spread. The variations in fuel map resolutions for the FARSITE simulations demonstrated the importance of an accurate resolution, besides the assignments of the correct fuel models. Coarse spatial resolution where a single fuel model is assigned to large polygons may not produce reliable fire spread predictions, because the homogeneous conditions assumed by the single fuel model do not reflect actual fuel variability across the large area (Finney, 1998). Furthermore, landscape-level fuel maps may describe with a high level of detail the distribution of vegetation type that differ in their fuel loads, for planning and implementing prescribed burns (Bailey and Mickler, 2007).

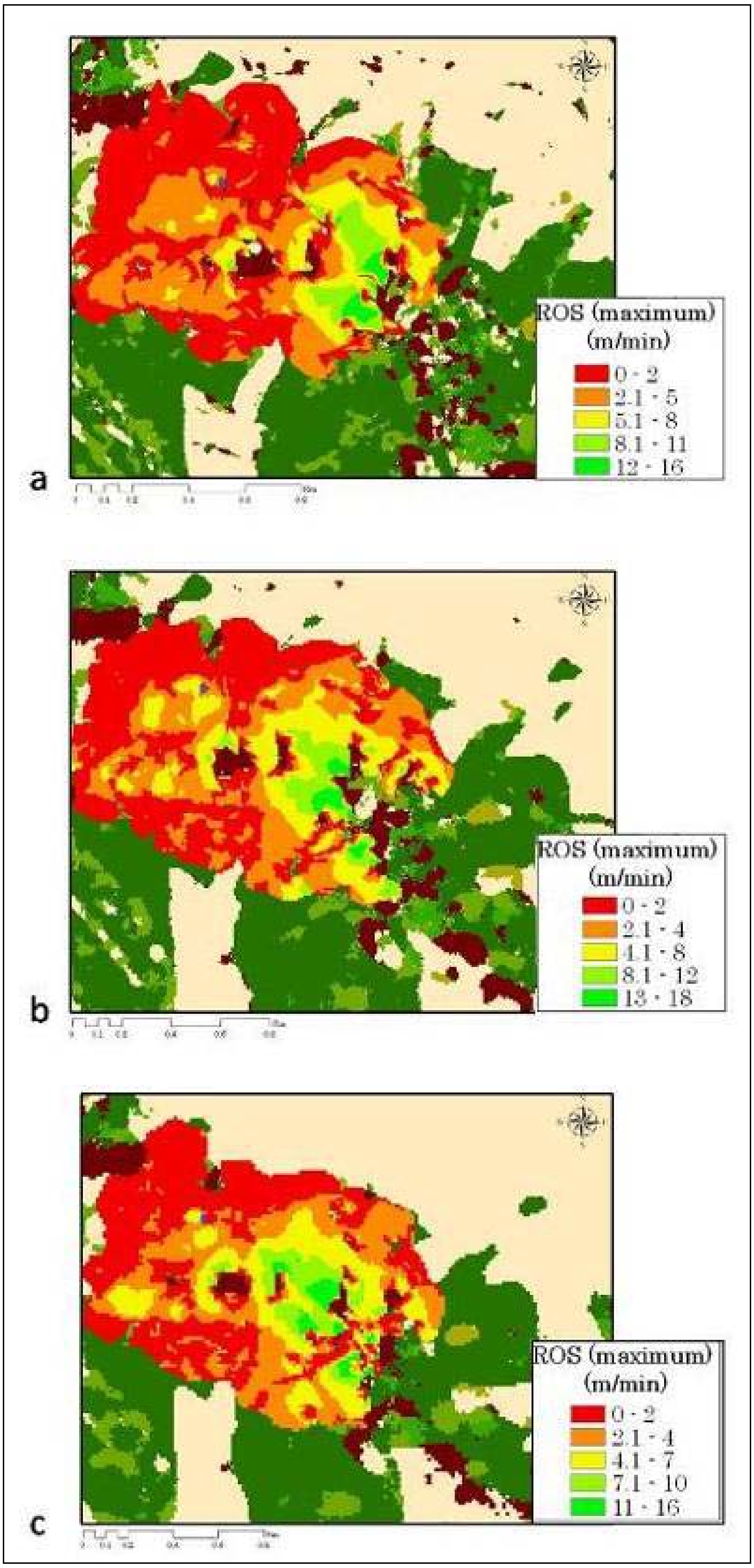


Figure 95. Rate of spread (ROS, m min^{-1}) predicted by simulation using a) fuel map resampled at 5 m; b) fuel map resampled at 10 m; c) fuel map resampled at 15 m. The wind was constant at 5 km h^{-1}

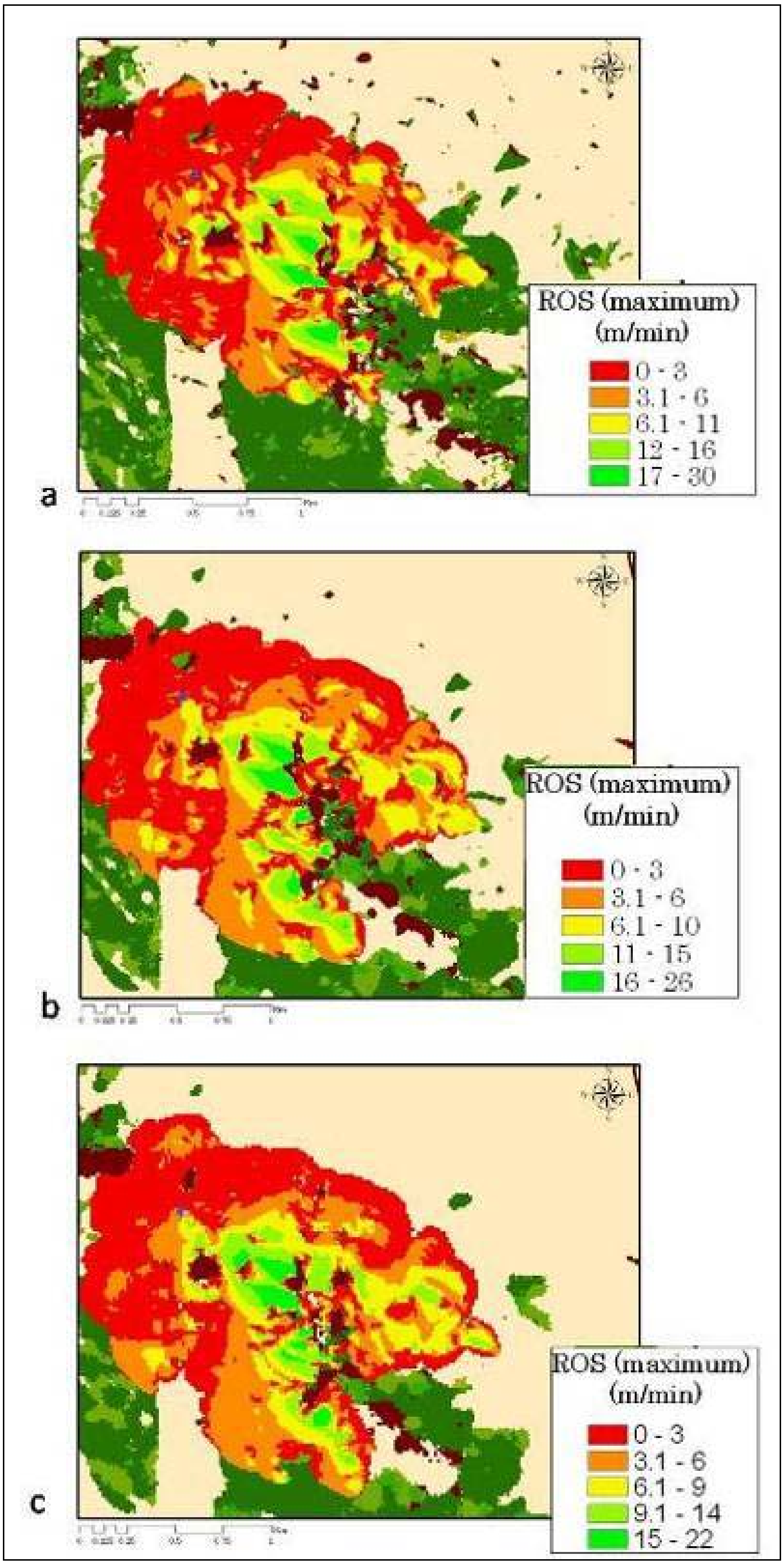


Figure 96. Rate of spread (ROS, m min^{-1}) predicted by simulation using a) fuel map resampled at 5 m; b) fuel map resampled at 10 m; c) fuel map resampled at 15 m. The wind was constant at 10 km h^{-1}

CONCLUSIONS

In several European countries, fuel load estimation and fuel models definition are relevant issues that need to be addressed in order to improve effectiveness of wildland fire prevention and management. This work was developed with the aim of focalizing on the major topics related to fuel: (i) the fuel complexes characterization, (ii) the analysis of the relationship between fuel complex properties and fuel load, (iii) the development of a set of fuel models for Mediterranean maquis, (iv) the development of maps of fuel models at local scale by analysis of remote sensed data, and finally (iv) the evaluation of the capabilities of fuel model themes and fuel map in simulating the fire spread and behaviour by spatially and temporal explicit fire simulators.

Several features, whose contribute to difference Mediterranean basin shrubland vegetation from those of the rest of Europe, must be taken in consideration when characterizing and mapping fuels. Firstly, the long and intense human impact (Pausas and Vallejo, 1999), having remarkable effects on the spatial homogeneity and leading to an intense fragmentation and degradation of shrubland areas. Secondly, the occurrence of the fire (often a recurrent feature) and disturbance regime, resulting in numerous effects on structural homogeneity, evolution stages and spatial distribution of different type of shrub vegetation, such as dense shrublands (dominated by multiple-stemmed woody species) or open scrublands (dominated by scrubs and grasses) (Pausas, 1999).

Thus, to characterize the fuel and obtain fuel maps, it became necessary to found large areas characterized by homogeneous cover, but with patches of burned surfaces, where the reoccurrence of the fire is probable, in order to consider the complex of fuel characteristics, rather than some Mediterranean shrub fuels (e.g. Countryman, 1982; Papiò and Trabaud, 1990; Pereira et al., 1995) or given community with one or two dominant species (e.g. De Luis et al, 2004; Viegas et al., 2006). The methodological approach to quantify fuel components and map fuel types, considering also the fuel conditions in presence of the afore-mentioned disturbs, can't set aside the ground survey such as destructive samplings, indispensable either as the basic source of data for parameterize each fuel type (Arroyo et al., 2008). Although these techniques are successful, they are time consuming and consequently economically unattractive (Falkowski et al., 2005), thus other easy and fast sampling methodologies should be used.

The Mediterranean shrublands (maquis) in Sardinia Island, characterized by several vegetation associations, does not make exceptions to the above mentioned features. Its evolution is strongly influenced by human disturbance, which had remarkable effects on the spatial and structural characteristics. Therefore, one of the major shortcomings during the development of this work was the localization of areas sufficiently extensive and characterized by homogeneous cover. Once individuate the areas, however, the sampling procedure was not easy, especially when high and close maquis was present. The destructive sampling is, as referred above, highly time consuming and expensive. For that reason, a part of the work focused on the ability of several parameters, easy to collect, to predict fuel loading of several components.

Experimental results regarding the characterization of the fuel complexes showed several trends commons in other Mediterranean areas, such as the high presence of the fine live component, consisting in green leaves and fine woody, with a percentage on the total shrub load about 35% in all sites. Obviously, in spite of this similar percentage in burned and unburned sites, quantitative differences were observed, not only regarding the fine live component, but also the other parameters. For example, burned sites are characterized by different litter load amount and average percent on total fuel (16%) compared to unburned areas (24%). The effect of the fire, that burn primarily fine fuel and litter, is particularly well evident, and it is important in the Mediterranean ecosystems, where litter decomposition may be very slow due to the coriaceous leaf structure of many species, their high concentration in secondary compounds, and the low moisture content of soils (Arianoutsou and Radea, 2000). However, it was interesting notice that for the majority of fuel parameter analyzed, the area burned in 1999 showed a completely different trend, nearest to unburned than burned areas. That is, it is possible to observe several changes, affecting the structure and the fuel load, mainly in the area burned in 1999, eight years before the experimental survey. Although these data referred to only five plots, similar results were found in literature. Baeza et al. (2004) referred that structural change in fuel characteristics are produced in short periods of time (3±9 years). Fernandes (1996) also described dramatic fuel modifications in short periods of time (4±8 years) in Portuguese shrublands. Therefore, also the results presented in this thesis appeared to confirm the existence of critical periods in shrubland development with structural changes producing fuel variability that can be relevant for fire behaviour.

Several regression analyses were performed for burned and unburned areas, in order to identify fuel parameters that explained the variation of the main fuel components. The relations between height and the fuel components were not highly satisfying, whereas the results showed that the equations with height multiplying cover (as a substitute of volume) were highly significant for all considered components, except for dead fine fuel load. In both cases the R^2 found considering the burned sites was higher than the unburned sites. This is probably due to structural changes driven by the fire, which increase the amount of light and water availability, and slow down the inter- and intra-specific competition, allowing to more species to grow. These results are in agreement with those published by other authors (Pereira, 1995; Usò et al., 1996; Fernandes and Rego, 1998; Saglam et al, 2008), highlighting that this first step to the development of non destructive index to quantify fuel components in burned and unburned areas is promising.

The variability that was noticed during the experimental survey in Mediterranean maquis was distinguished by cluster analysis techniques in terms of fuel load categories and vegetation structural parameters in four fuel classes, as reported by Dimitrakopoulos (2002) and Van Hees et al. (2001). Thus, four fuel type classes were identified using an adaptation of Prometheus classification system. Custom fuel models for Mediterranean maquis were subsequently standardized from fuel type, basing normally upon the size, species, form, arrangement, and continuity of constituent fuel elements (Merrill and Alexander, 1987). We developed custom fuel model not only for close maquis fuel types, but also for low and open maquis, typical of recently disturbed areas, due to fire, grazing, and cutting. The fuel values represented by the models fall well within the range reported for Mediterranean vegetation types in other parts of the world: the custom fuel model representing the "high and close" maquis type is characterized by a live to dead fuel ratio almost similar to that evidenced by the standard fuel models FM4 by Anderson (1982), and SH7 by Scott and Burgan (2005), as well as the other fuel models, representing "medium height and close" and "medium" maquis. Nevertheless the similarity, the simulated fire behaviour are different: FM4 predicts faster spread rates than CM4, in dry moisture conditions, whereas SH7 predicts lower spread rates, despite higher fuel load. Weise and Regelbrugge (1997) reported an overestimation of actual fire spread in chaparral using the standard fuel model FM4. Moreover, the parameters of the custom fuel model here developed are in agreement with several studies conducted to determine the fuel types of Mediterranean basin vegetation. Dimitrakopoulos (2002) reported two fuel models relative to evergreen-sclerophyllous shrublands, similar in fuel load to CM2 and CM3, with similar potential fire behaviour in most conditions. 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.

One of the limits of the stylized fuel models is that they allow only general fire behaviour predictions that may substantially vary from on area to another, depending on the local fuel conditions. Moreover, an important limit is that custom fuel model could be unsuccessful when developed without calibrating the prediction or tuning the parameters against fire behaviour observation, as highlighted by Cruz and Fernandes (2008). In this work no comparison with observed fire behaviour was made, in principal because the databases of actual fires occurred in Sardinia does not collect the parameters needed for the estimate of rate of spread, fire line intensity, and flame length.

The classification of various vegetation types into standardized fuel model is an important component of wildland fire management worldwide (Pyne et al., 1996). Vegetation and fuel types in southern Europe are frequently assigned at NFFL fuel model, e.g. ICONA (1990). According to several authors (van Wilgen et al., 1985; Dimitrakoupoulos, 2002), specific custom models need to be developed to account for both the fuel characteristics and the high heterogeneity of shrubland vegetation. Van Wilgen et al. (1985) suggested the development of different custom fuel models to accurately describe the heterogeneous structural types of *fynbos*.

The supervised classification of IKONOS images performed in this study produced a reasonably accurate mapping of fuel type, achieving overall accuracy of 72%. One of the main problems was to identify and differentiate the “woody” fuel types from the four maquis fuel type, in particular from “high and close” maquis. Another source of error was about the “low and open” maquis, which was underestimated; some pixels were misclassified as “agriculture and pasture”. Moreover, several commission errors were made between “medium height and close” and “medium” maquis: probably this is due to the reflectance, not directly related to vegetation height, which is a critical variable to discriminate among fuel types. Future fuels mapping efforts may be more successful by integrating multispectral satellite data with hyperspectral data, LiDAR data, or both, to avoid misclassifications by retrieving more direct information on vegetation height. However, the availability of low-cost satellite hyperspectral and LiDAR datasets is currently limited (Falkowsky et al., 2005). Another problem was due to the high spatial resolution that increased the spectral within-field variability. As the matter of fact, contrary to coarse resolution, where signature of interest become convolved with neighbouring signatures, the too fine resolution involve that signatures correspond only to components of the features of interest, leaving the *post facto* task of combining components (Arroyo et al., 2006). This behaviour was noticed also by other authors (Blaschke and Strobl, 2001; Sawaya et al., 2003; van der Sande et al., 2003). Further studies should be conducted on several methodologies attempting to overcome this problem, such as the object-oriented approach (Arroyo et al., 2006; Giakoumakis et al., 2002).

Due to the complex nature of fuel characteristics a fuel map is considered one of the most difficult thematic layers to build up (Keane et al., 2000, 2001). The high fuel variability across time and space is probably the main condition that confounds, affecting fuel mapping accuracy (Arroyo et al., 2008). Aerial photos have been the most common remote sensing data source for mapping fuel type’s distribution (Morris, 1970; Muraro, 1970; Oswald et al, 1999; Caria, 2004; Salis, 2008; Arca et al., 2007; Salis et al., in press). Nevertheless, several authors pointed out the limitations to distinguish, through photo-interpretation, the internal differences of the fuel complex, their spatial distribution and cover heterogeneity at fine scale; whereas remote sensing from satellite multispectral data can be an effective data source to capture the spatial heterogeneity (Lasaponara and Lanorte, 2007; Keane et al., 2001). New sensors such as Quickbird and IKONOS have provided meter spatial resolution, and have been widely applied in vegetation characterization (Wang et al., 2004; Hyde et al., 2006; Mallinis et al., 2008), but few works have focused on this source of information for map fuel type (Lasaponara and Lanorte, 2007).

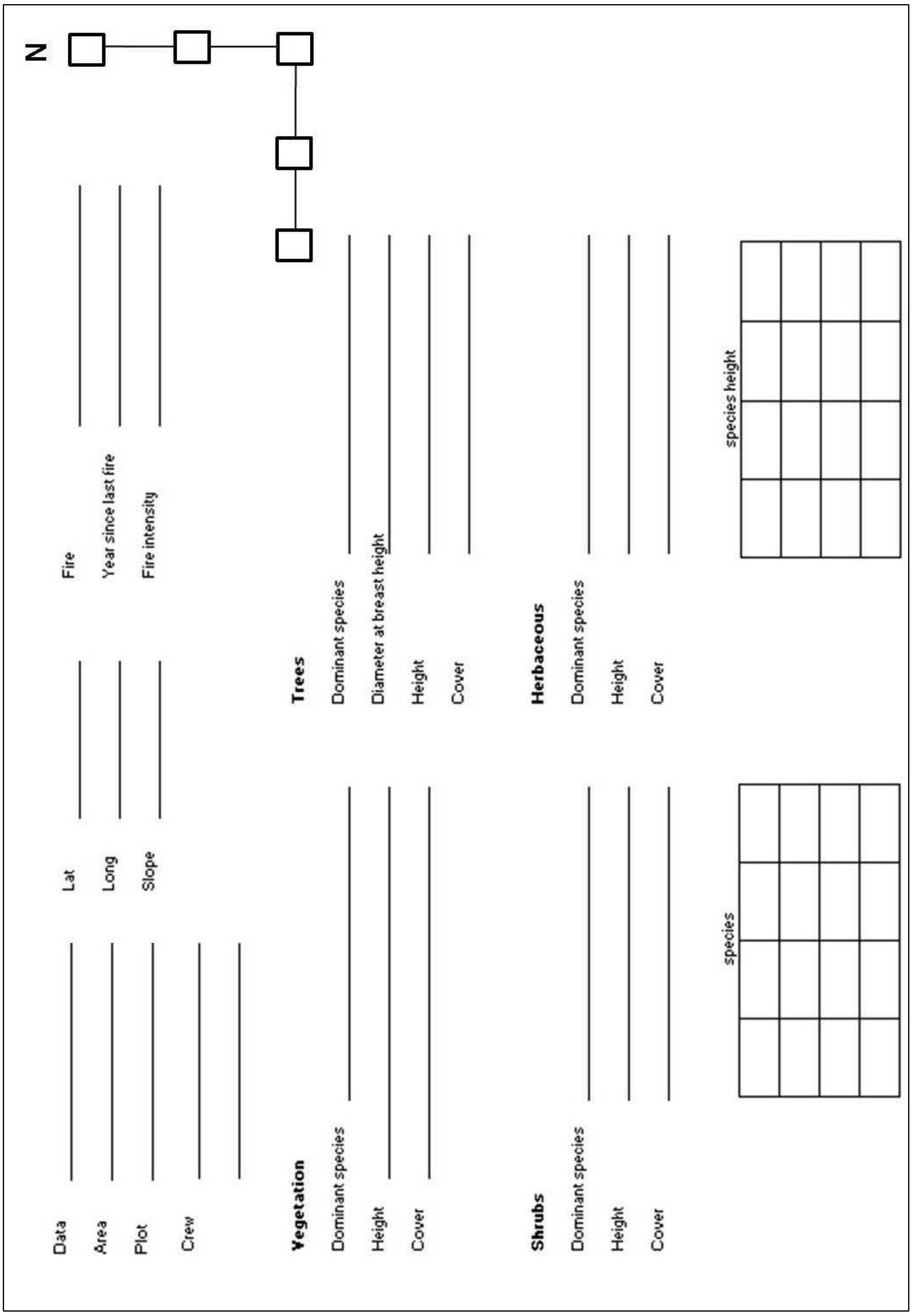
Fuel maps as that produced in this study are essential for local fire management because they also describe fire potential for planning and prioritizing specific burn projects (Chuvieco and Congalton 1989; Pala et al. 1990; Maselli et al. 1996). More importantly, such maps can be used as inputs to spatially explicit fire growth for purposes of fighting wildland fire (Andrews et al., 2003) or predicting the effect of fuel reduction treatments (Stratton, 2004).

Thus, the capabilities of fuel map themes in simulating the fire spread and behaviour by spatially and temporal explicit fire simulators were performed. This thesis showed that the resolution of fuel map data affected the performance of FARSITE simulator. Custom fuel models developed from fuel sampling were used to crosswalk from the IKONOS fuel type map to fuel model map and re-sampled at three fine resolutions, less than 20 m pixel. The results among the fuel maps showed that the maximum and average rate of spread and the area burned (in ha) changed due scale resolution, that is, FARSITE was sensitive to the change in fuel map resolution. The results for rate of spread increased especially for low intensity wind speed, whereas the burned area (ha) increased for moderate intensity wind speed from 5 m to 15 m map. In this study, the simulations using the three fuel map created a baseline to understand how fire would react in Mediterranean areas using fuel map with different fine resolution scale.

In several works is referred that the accuracy of FARSITE can be improved using custom fuel model, designed and developed with the purpose of simulating the fire spread and behaviour on a particular type of vegetation (Van Wilgen et al., 1985; Weise and Regelbrugge, 1997; Fernandes, 2001); the results showed previously pointed out that the developed custom fuel models were similar to those presented by the standard fuel model of Anderson (1982) and

Scott and Burgan (2005). Other studies suggested that the accuracy can be improved using high resolution and accuracy wind data (Hanson et al., 2000). Several works pointed out that fuel maps must be developed at fine resolution, in order to obtain realistic simulations of fire spread and behaviour (Finney, 2005; Keane, 2002). High profile fuel mapping projects are more able to capture fine scale fuel distributions for accurate fire growth projections. In effect, using coarse spatial resolutions (up to 30 m pixel) it is easy to assign a single fuel model to large polygons, affecting the reliability of fire spread predictions, because the homogeneous conditions assumed by the single fuel model do not reflect actual fuel variability across the large areas (Finney, 1998). Moreover, as fuel maps increase in grain and extent the variation of fuel characteristics is often lost. As a result, intra-stand variation in fire behaviour will not be simulated and this may eventually cause inaccurate fire growth calculations (Keane et al., 2001).

APPENDIX



Appendix 1. Plot description form, regarding the main descriptors of the plots. The plot (2x2 m) was subdivided into 16 quadrants, where the height (as the vertical average distance from the soil surface to the top of the branches) and the cover of the predominant species were surveyed

Area	Plot	Data	coord. point 0	coord. point 1	Direction	slope
point	***Distance***	***Specie***	***count***	***mean height***	***dead material***	

Appendix 2. Transect form. Plant *cover* was sampled by the line intercept method, in which the length of intercept for each plant species was measured along a tape by recording the point on the tape where the plant canopy begins and the plant canopy ends. Plant *height* was collected along transects by measuring the vertical distance from the soil surface to the top of the branches. Measurements were performed every 10 cm.

Data ____________ Lat ____________ **Litter** sample n° ________

Area ____________ Long ____________ Fresh weight ____________

Plot ____________ Slope ____________ Sample weight ____________

Crew ____________ Dry weight ____________

____

Downed woody 1 hr

Total Fresh weight ____________

Sample fresh weight ____________

Sample dry weight ____________

Downed woody 10 hr

Total Fresh weight ____________

Sample fresh weight ____________

Sample dry weight ____________

Downed woody 100 hr

Total Fresh weight ____________

Sample fresh weight ____________

Sample dry weight ____________

Specie ____________

Live 1 hr

Total Fresh weight ____________

Sample fresh weight ____________

Sample dry weight ____________

Live 10 hr

Total Fresh weight ____________

Sample fresh weight ____________

Sample dry weight ____________

Live 100 hr

Total Fresh weight ____________

Sample fresh weight ____________

Sample dry weight ____________

Dead 1 hr

Total Fresh weight ____________

Sample fresh weight ____________

Sample dry weight ____________

Dead 10 hr

Total Fresh weight ____________

Sample fresh weight ____________

Sample dry weight ____________

Dead 100 hr

Total Fresh weight ____________

Sample fresh weight ____________

Sample dry weight ____________

Appendix 3. Fuel load form, comprehensive of the litter and downed woody surveyed into the plot, and the live and dead woody in the different size categories for each specie comprised within the fuel bed

Data ______________________
Area ______________________
Crew ______________________

Point n° | **Dominant species** | **Height** | **Cover**

Latitude ________ **Cover** ________
Longitude ________ **Height** ________
Slope ________ **Fuel type** ________

mean *min* *max*

Point n° | **Dominant species** | **Height** | **Cover**

Latitude ________ **Cover** ________
Longitude ________ **Height** ________
Slope ________ **Fuel type** ________

mean *min* *max*

Point n° | **Dominant species** | **Height** | **Cover**

Latitude ________ **Cover** ________
Longitude ________ **Height** ________
Slope ________ **Fuel type** ________

mean *min* *max*

Point n° | **Dominant species** | **Height** | **Cover**

Latitude ________ **Cover** ________
Longitude ________ **Height** ________
Slope ________ **Fuel type** ________

mean *min* *max*

Appendix 4. Ground thruth nondestructive measurements data form. Measurements at each site included: position data collected by a differential correction GPS, average cover and height of the area, dominant species, plant height (mean, min, and max) and cover degree of shrubs.

REFERENCES

Adams J.L., 1965. *Fuel Classification and Mapping for Forest Fire Control*. University of California, Berkeley.

Agee J.K., Pickford S.G., 1985. *Vegetation and fuel mapping of North Cascades National Park*. Final Report. College of Forest Resources, University of Washington, Seattle, Wash.

Agee JK., Huff MH., 1987. *Fuel succession in a western hemlock/ Douglas-fir forest*. Canadian Journal of Forest Research 17(7), 697-704.

Ahern F.J., Janetos A.C., Langham E., 1998. Global observation of forest cover: One component of CEOS' Integrated Global Observing Strategy, 27th International Symposium on Remote Sensing of Environment, Tromsø, Norway.

Albini F.A., 1976. *Estimating Wildfire Behaviour and Effects*. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-30. Odgen, UT, 74 pp..

Albini F.A., 1979. *Spot Fire Distance from Burning Trees: a Predictive Model*. USDA Forest Service General Technical Report. Research Paper INT-56.

Albini F.A., 1980. *Thermochemical properties of flame gases from fine wildland fuels*. USDA Forest Service. Intermuntain Forest and Range Experimental Station, research paper, INT-243, Odgen, Utah, USA

Albini F.A., Reinhardt E.D., 1995. *Modeling ignition and burning rate of large woody natural fuels.* International Journal of wildland Fire 5, 81-91.

Almeida A.F., Fernandes P., Pereira J.P., 1995. *Série fotográfica dos modelos de combustível da Serra da Arrábida*. Silva Lusitana 3(2).

Amanatidis G.T., Paliatsos A.G., Repapis C.C., Bartzis J.G., 1993. *Decreasing precipitation trend in the Marathon area, Greece*. International Journal of Climatology 13, 191-201

Anderson D.R., Laake J.L., Crain B.R., Burnham K.P., 1979. *Guidelines for line transect sampling of biological populations*. Journal of Wildland Management 43,70-78.

Anderson G.L., Everitt J.H., Richardson A.J., Escobar D.E., 1993. *Using satellite data to map false broomweed (*Ericamera austrotexana*) infestations on south Texas rangelands*. Weed Technology 7, 865–871.

Anderson H.E., 1982. *Aids to Determining Fuel Models for Estimating Fire Behaviour.* USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report, INT-122.

Andrews P.L. 2007. *BehavePlus fire modeling system: past, present, and future.* In 'Proceedings of 7th Symposium on Fire and Forest Meteorological Society', 23-25 October 2007, Bar Harbor, Maine, 13 p.

Andrews P.L. 2007. *BehavePlus fire modeling system: past, present, and future.* In 'Proceedings of 7th Symposium on Fire and Forest Meteorological Society', 23-25 October 2007, Bar Harbor, Maine, 13 p.

Andrews P.L., 1980. *Testing the fires behavior model. P. 70 in Proc.* Sixth Conf. on Fire and For. Meteorol. Seattle, WA.

Andrews P.L., 1986. BEHAVE: *Fire Behaviour Prediction and Fuel Modeling System - BURN Subsystem, Part 1.* USDA Forest Service General Technical Report INT-194.

Andrews P.L., Bevins C.D., 1998. *Update and Expansion of the BEHAVE Fire Behavior Prediction System.* USDA Forest Service, Rocky Mountain Research Station

Andrews P.L., Bevins C.D., Seli R.C., 2005. *BehavePlus Fire Modeling System, Version 3.0: User's Guide.* General Technical Report RMRS-GTR-106WWW Revised. Ogden, UT: USDA, Forest Service, Rocky Mountain Research Station. 132 pp..

Andrews P.L., Bradshaw L.S., 1990. *RXWINDOW: defining windows of acceptable burning conditions based on desired fire behaviour.* USDA Forest Service. Intermuntain Forest and Range Experimental Station, research paper, INT-273, Odgen, Utah, USA

Andrews P.L., Chase C.H., 1989. *BEHAVE: fire behaviour prediction system-BURN subsystem Part 2. USDA Forest Service.* Intermuntain Forest and Range Experimental Station, research paper, INT-260, Odgen, Utah, USA

Andrews P.L., Loftsgaarden D.O., Bradshaw L.S., 2003. *Evaluation of fire danger rating indexes using logistic regression and percentile analysis.* International Journal of Wildland Fire, 12, 213-226.

Andrews P.L., Queen L.P., 2001. *Fire modeling and information system technology.* International Journal of Wildland Fire 10:343-352

Andrews P.L., Rothermel R.C., 1982. *Charts for Interpreting Wildland Fire Behaviour Characteristics.* General Tech. Report INT-131. Ogden, UT: USDA, Forest Service, Intermountain Forest and Range Experiment Station. 21 pp..

Arca B., Duce P., Laconi M., Pellizaro G., Salis M., Spano D., 2007. Evaluation of FARSITE simulator in Mediterranean maquis. International Journal of Wildland Fire 16, 563-572.

Arca B., Laconi M., Maccioni A., Pellizzaro G., Salis M., 2005. *Validation of FARSITE Model in Mediterranean Area*. In Proceedings of the 6th Fire and Forest Meteorology Symposium; 2005, October 25-27, Canmore, AB, Canada.

ArcGis 9, ESRI Inc., Redlands, CA, USA

Arianoutsou M., Radea C., 2000. *Litter production and decomposition in Pinus halepensis forest, in: G.* Ne'eman, L. Trabaud (Eds.), Ecology, Biogeography, and Management of Pinus Halepensis and P. Brutia Forest Ecosystems in the Mediterranean Basin, Backhuys Publishers, Leiden, The Netherlands, 2000, pp. 183–190.

Arianoutsou M., Thanos C.A., 1996. *Legumes in the fire-prone Mediterranean regions: an example from Greece.* International Journal of Wildland Fire 6, 77-82.

Arno, S. F. 1976. *The historical role of fire on the Bitterroot National Forest*. USDA Forest Service Research Paper INT-187. Intermountain Forest and Range Experiment Station, Ogden, Utah, USA.

Arroyo L., Healey S.P., Cohen W.B., Cocero D., Manzanera J.A., 2006. *Using object-oriented classification and high-resolution imagery to map fuel types in a Mediterranean region*. Journal of Geophysical Research. Vol. 111, G04S04, doi:10.1029/2005JG000120, 2006

Austin M.P., 1984. *New approaches to direct gradient analysis using environmental scalars and statistical curve-fitting procedures*. Vegetatio 55,11-21

Austin M.P., 1987. *Models for the analysis of species' response to environmental gradients*. Vegetatio 69, 35-45

Austin M.P., Cunningham R., Good R.B., 1983. *Altitudinal distribution of several eucalypt species in relation to other environmental factors in southern New South Wales*. Australian Journal of Ecology 8, 169-180.

Austin M.P., Smith T.M., 1989. *A theory of spatial and temporal dynamics in plant communities.* Vegetation 83:49–69.

Baeza M.J., De Luis M., Raventós J., Escarré A., 2002. *Factors influencing fire behaviour in shrublands of different stand ages and the implications for using prescribed burning to reduce wildfire risk*. Journal of Environment Management 65, 199–208.

Baeza M.J., Raventós J., Escarré A., 1998. *Structural changes in relation to age in fire-prone Mediterranean shrublands.* In Proceedings of the International Conference on Forest Fire Research, (Ed. DX Viegas), Vol. 2, Coimbra, pp. 2567-2578.

Bailey A.D., Mickler R., 2007. *Fine scale vegetation classification and fuel load mapping for prescribed burning*. In Butler, Bret W.; Cook, Wayne, comps. The fire environment--innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of

Agriculture, Forest Service, Rocky Mountain Research Station. CD-ROM. p. 261-273.

Bailey R.G., 1995. *Description of the Ecoregions of the United States*. 2nd ed. rev. and expanded (1st ed. 1980). Misc. Pub. No. 1391 (rev.). Washington, DC: USDA Forest Service. 108 pp., with separate map at 1:7,500,000.

Barrett S.W., Arno S.F., 1993. *Classifying fire regimes and defining their topographic controls in the Selway–Bitterroot Wilderness*. In Proceedings of the 11th conference on fire and forest meteorology. (Eds PL Andrews and DF Potts) pp. 299–307. (Society of American Foresters: Bethesda, MD)

Barrows J.S., 1951. *Fire Behavior in Northern Rocky Mountain Forests*. U.S. Forest Service, Northern Rocky Mountain Forest and Range Experiment Station, Paper 29.

Barton A.M., 1994. *Gradient analysis of relationship among fire, environment, and vegetation in a southwestern USA mountain range*. Bulletin of the Torrey Botanical Club 121, 251-265.

Bertolette D.R., Spotskey D.B., 1999. *Fuel model and forest type mapping for FARSITE. In: The Joint Fire Science Conference and Workshop*. University of Idaho and International Association of Wildland Fire, Boise, Idaho.

Bianchi M., 1997. *Quale inventario inventare?* Monti e Boschi 5, 2-3.

Biswell H.H., 1989. *Prescribed Burning in California Wildlands Vegetation*. Berkeley, CA: University of California Press.

Blaschke T., Strobl J., 2001. *What's wrong with pixels? Some recent developments interfacing remote sensing and GIS.* GIS - Zeitschrift fur Geoinformationssysteme 6, 12–17.

Bobbe T., Lachowski H., Maus P., Greer J., Dull C., 2001. *A primer on mapping vegetation using remote sensing*. International Journal of Wildland Fire 10, 277–287.

Bond W.J., van Wilgen B.W., 1996. *Fire and plants*. (Chapman and Hall: London)

Bonham C.D., 1989. *Measurements for Terrestrial Vegetation*. Wiley, New York

Boni C., 2004. *Il Fenomeno degli Incendi in Sardegna*. Atti del Convegno "Incendi Boschivi e Rurali in Sardegna-Dall'Analisi delle Cause alle Proposte di Intervento", pag. 9-17. Cagliari, Maggio 2004.

Bray J.R., Curtis J.T., 1975. *An ordination of the upland forest communities of Southern Wisconsin*. Ecological Monographs 27, 325–349.

Brown A.A., Davis K.P., 1973. *Forest Fires Control and Use*. McGraw Hill, 2nd Edition, New York, 686 pp..

Brown J.K. 1971. *A planar intersect method for sampling fuel volume and surface area*. Forest Science 17(1), 96-102.

Brown J.K. 1976. *Estimating shrub biomass from basal stem diameters*. Canadian Journal of Forest Research 6(2), 153-158.

Brown J.K., 1970. *A method for inventorying downed woody fuel*. USDA Forest Service General Technical Report INT-16. 24 pp.

Brown J.K., 1970a. *Physical fuel properties of ponderosa pine forest floors and cheatgrass*. USDA Forest Service. Intermuntain Forest and Range Experimental Station, research paper, INT-74, Odgen, Utah, USA

Brown J.K., 1970b. *Ratios of surface area to volume for common fine fuels*. Forest Science 16, 101-105

Brown J.K., 1974. *Handbook for inventorying downed woody material.* USDA Forest Servive General Techical Report, INT-16, ntermuntain Forest and Range Experimental Station, Ogden,Utah.

Brown J.K., 1981. *Bulk densities of nonuniform surface fuels and their application to fire modeling*. Forest Science 27, 667-783.

Brown J.K., Bevins C.D., 1986. *Surface fuel loadings and predicted fire behavior for vegetation types in the northern Rocky Mountains.* USDA Forest Service, Intermountain Forest and Range Experiment Station Research Note INT-358. Ogden, UT. 9 pp.Brown and Davis, 1973

Brown J.K., See T.E., 1981. *Downed dead woody fuel and biomass in the northern Rocky Mountains.* USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report INT-117. Ogden, UT. 48 pp.

Browning B.L., 1963. The chemistry of wood. ed., Interscience, New York, 689 pp. Cellulose Research Institute, State University College of Forestry, Syracuse University, Syracuse, New York.

Buech R.R., Rugg D.J., 1989. Biomass relation of shrub component and their generality. Forest Ecology and Management 26, 27-264

Buell M.F., Cantlon J.E., 1950. *A study of two communities of the New Jersey Pine Barrens and a comparison of methods*. Ecology 31: 567–586.

Burgan R. E. 1979. *Estimating live fuel moisture for the 1978 national fire danger rating system*. General Technical Report -INT-226, USDA Forest Service, Ogden, UT.

Burgan R.E., 1987. *Concepts and Interpreted Examples in Advanced Fuel Modeling*. USDA Forest Service General Technical Report INT-238.

Burgan R.E., Klaver R.W., Klaver J.M., 1998. *Fuel models and fire potential from satellite and surface observatio*ns. International Journal of Wildland Fire 8(3), 159–170.

Burgan R.E., Rothermel R.C., 1984. *BEHAVE: Fire Behaviour Prediction and Fuel Modeling System - FUEL Subsystem*. USDA Forest Service General Technical Report INT-167.

Burnham K.P., Anderson D.R., Laake J.L., 1980. *Estimation of density from line transect sampling of biological populations*. Wildlife Monographs 72, 1-202.

Bussotti F., Piccini C., Piotto B., Cervelli C., 2005. *La macchia mediterranean: la vegetazione e il suo rapporto con l'uomo*. In Le specie arbustive della macchia mediterranea, un patrimonio da valorizzare. Eds Azienda Regionale Foreste Demaniali Regione Sicilia

Bussotti F., Schirone B., 2001. *La Vegetazione Mediterranea*. In: Piotto B., Di Noi A. (eds.), "Propagazione per Seme di Alberi e Arbusti della Flora Mediterranea". Manuale ANPA.

Byram G.M., 1959. *Chapter Three, Combustion of Forest Fuels*. In Davis .K.P., "Forest Fire: Control and Use". McGraw-Hill. New York.

Canadian Forestry Service. 1987. Tables for the Canadian Forest Fire Weather Index System. Can. For. Serv., For. Tech. Report No. 25 (4th edition). Ottawa, ON.

Canadian Interagency Forest Fire Centre. 2002. The 2002 glossary of forest fire management terms. Available at http://wlapwww .gov.bc .ca/esd/fire_mgmt gloss_2002.pdf.Caratti, 2006

Caratti J. F. 2006. *The LANDFIRE reference database*. Pp. 69-98 In: Rollins, M.G.; and C.K. Frame, tech. eds. 2006. The LANDFIRE Prototype Project: nationally consistent and locally relevant geospatial data for wildland fire management. Gen. Tech. Rep. RMRS-GTR-175.. U.S. Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado.

Caria C.A., 2003. *Implementazione e Adattamento del Simulatore di Propagazione degli Incendi FARSITE in Ambiente Mediterraneo*. PhD. Thesis. Università degli Studi di Sassari, Dipartimento di Economia e Sistemi Arborei, 80 pp..

Castro R., Chuvieco E., 1998. *Modelling forest fire danger from geographic information system*. Geocarto Int. 13, 15–23.

Chandler C., Cheney N.P., Thomas P., Trabaud L., Williams D., 1983. *Fire in Forestry - Forest Fire Behaviour and Effects.* Ed. John Wiley & Sons. Vol. 1.

Chandler C., Cheney P., Thomas P., Trabaud L., Williams D., 1993. *Fire in forestry, Volume I: Forest fire behaviour and effects*. (Hohn Wiley and Sons: New York)

Cheney N.P., 1996. *The effectiveness of fuel reduction burning for fire management. In Fire and biodiversity, the effects and effectiveness of fire management.* Footscray, Melbourne pp. 9-18 (Biodivesity Unit)

Cheney P., 1992. *A National Fire Danger Rating System for Australia*. International Forest Fire News, (No. 6 - January 1992)[OL]. Available at: http://www.fire.uni-freiburg.de/iffn/country/au/au 4.htm.

Chessa P.A., Delitala A., 1997. *Il Clima della Sardegna. Servizio Agrometeorologico Regionale (SAR) per la Sardegna, nota tecnica n° 2.* http://www.sar.sardegna.it/pubblicazioni/notetecniche/nota2/index.asp.

Chladil M.A., Nunez M., 1995. *Assessing grassland moisture and biomass in Tasmania*. The application of remote sensing and empirical models for a cloudy environment. International Journal of Wildland Fire 5(3), 165–171.

Chuvieco E., Congalton R.G., 1989. *Application of remote sensing and geographic information systems to forest fire hazard mapping*. Remote Sensing of the Environment 29, 147–159.

Chuvieco E., Martin M.P., 1994. *Global fire mapping and fire danger estimation using AVHRR images*. Photogrammetric Engineering and Remote Sensing 60(5), 563–570.

Chuvieco E., Riano D., Morsdorf F., 2003. Fuel Loads and Fuel Type Mapping. In Chuvieco, E. (ed.): Wildland Fire Danger Estimation and Mapping - The Role of Remote Sensing Data; , pp. 119-142., World Scientific.

Chuvieco E., Salas J., Vega C., 1997. *Remote sensing and GIS for longterm fire risk mapping*. In 'A review of remote sensing methods for the study of large wildland fires'. (Ed. E Chuvieco) pp. 91–108. Megafires Project ENV-CT96-0256. Alcala de Henares, Spain.

Chuvievo E., Riano D., Morsdorf F., 2003. *Fuel Loads and Fuel Type Mapping*. In Chuvieco, E. (ed.): Wildland Fire Danger Estimation and Mapping - The Role of Remote Sensing Data; , pp. 119-142., World Scientific.

Clar C.R., Chatten L.R., 1966. *Principles of Forest Fire Management*. Sacramento, CA: Office of Procurement, State of California.

Cohen W.B., Harmon M.E., Wallin D.O., Fiorella M., 1996. *Two decades of carbon flux from forests of the Pacific Northwest: estimates from a new modeling strategy*. Bioscience 46(11), 836–844.

Colacino M., Conte M., 1993a. Andamento della temperatura dell'aria in Italia dalla seconda metà del secolo scorso ad oggi. Bollettino Geofisico, XVI-1, 777.

Colacino M., Conte M., 1993b. Greenhouse effect and pressure pattern in the Mediterranean basin. Il Nuovo Cimento, 16C, 67-76.

Congalton R., 2001. Accuracy assessment and validation of remotely sensed and other spatial information. The International Journal of Wildland Fire. Vol 10. pp. 321-328.

Congalton R.G., 1991. *A review of assessing the accuracy of classifications of remotely sensed data.* Remote Sensing of the Environment 37, 35–46.

Congalton R.G., Green K., 1999. *Assessing the accuracy of remotely sensed data: Principles and practices.* (Lewis Publishers, CRC Press: Boca Raton) 137 pp.

CORINE land cover - *Technical Guide, 1994*. Publication EUR 12585 of the European Commission, EG, DG Environment, Nuclear Safefy, and Civil Protection. Luxembourg: Office for official publications of the European Communities.

Corona P., 2000. *Introduzione al rilevamento campionario delle risorse forestali*. Edizioni Cusl. Firenze

Corpo Forestale dello Stato, 2007. *Campagna Antincendi Boschivi 2007.* http://www2.corpoforestale.it/web/guest/serviziattivita/antincendioboschivo/iniziativesperimentazioni/campagna07.

Countryman C.M., 1982. *Physical characteristics of some Northern California brush fuels*. USDA Forest Service General Techical Report PSW-61, Pacific Southwest Forest and Range Exp. Stn. Berkeley, California.

Countryman C.M., Philpot C.W., 1970. *Physical characteristics of chamise as a wildland fuel*. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Research Paper, PSW-66, Berkeley, California, USA

Cruz M.G. 2005. *Guia Fotográfico para Identificação de Combustíveis Florestais- Região Centro de Portugal.* Centro de Estudos sobre Incêndios Florestais-ADAI, Coimbra. 38 pp..

Cruz M.G., Fernandes P., 2008. *Development of fuel models for fire behaviour prediction in maritime pine (Pinus pinaster Ait.)* stands. International Journal of Wildland Fire 17, 194–204.

Curry J.R., Fons W.L., 1938. *Rate of spread of surface fires in Ponderosa pine type of California.* Journal of Agricultural Research 57, 239-268.

Daubenmire R., 1966. *Vegetation: identification of typical communities*. Science 151, 291–298.

Daubenmire R., 1968. *Ecology of fire in grasslands*. In: Cragg,J.B. ed.Advances in ecological research.Vol.5. New York, NY: Academic Press: 209-266.

Davis F.W., Goetz S., 1990. *Modeling vegetation pattern using digital terrain data.* Landscape Ecology 4(1), 69–80.

Davis J.R., Dieterich J.H., 1976. *Predicting rate of fire spread (ROS) in Arizona oak chaparral: Field workbook*. General Technical Report INT-24. Fort Collins, CO. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station.

Davis K.P., 1959. *Forest fire: control and use*. McGraw-Hill, New York.

De Luis M., Baeza M.J., Raventós J., Hidalgo J.C.G.. 2004a. *Fuel characteristics and fire behavior in mature Mediterranean gorse shrublands*. International Journal of Wildland Fire. 13, 79-87.

De Luis M., Raventós J., Cortina J., González-Hidalgo J.C., Sánchez J.R.. 2004b. *Fire and torrential rainfall: effects on the perennial grass Brachypodium retusum*, Plant Ecology 173, 225–232.

De Philippis A., 1937. Classificazioni ed indici del clima in rapporto alla vegetazione forestale italiana. Nuovo Giornale Botanico Italiano XLIV, 1–169.

De Wulf R.R., Goossens R.E., Roover B.P., Borry, F.C., 1990. *Extraction of forest stand parameters from panchromatic and multispectral SPOT-1 data [J].* International Journal Remote Sensing, 11, 1571-1588.

DeBano L., Neary D., Ffolliott D.G., 1998. *Fire's Effects on Ecosystems*. New York: John Wiley & Sons, Inc., 333 p..

Decreto Legislativo 18 maggio 2001, n. 227. Orientamento e modernizzazione del settore forestale, a norma dell'articolo 7 della legge 5 marzo 2001, n. 57. Pubblicato nella Gazzetta Ufficiale n. 137 del 15 giugno 2001 - Supplemento Ordinario n. 149

Deeming J.E., 1975. *Fuel Models in the National Fire Danger Rating System*. Journal of Forestry 73(6), 347-350.

Deeming J.E., Burgan R.E., Cohen J.D., 1977. *The National Fire Danger Rating System*. Report No. GTR INT-39. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Deeming J.E., Burgan R.E., Cohen J.D., 1978. *The National Fire Danger Rating System*. USDA Forest Service General Technical Report.

Deeming J.E., Lancaster J.W., Fosberg M.A., Furman R.W., Schroeder M.J., 1972. Revised 1974. *The National Fire-Danger Rating System.* Report No. RM-84. USDA Forest Service, Ogden, UT.

Deitschman G.H., 1973. *Mapping of habitat types throughout a national forest*. USDA Forest Service General Technical Report INT-11. 14 pp.

DGF, 2001. *Inventário Florestal Nacional: Portugal Continental* 3ª revisão. Lisboa.

Di Castri F., 1981. *Mediterranean-type shrublands of the world*. In Di Castri F, Goodall DW, Specht RL eds. Mediterranean-Type shrublands. Amsterdam, Elsevier, pp. 1-52.

Di Castri F., Mooney H.A., (eds), 1973. *Mediterranean-Type Ecosystems. Origin and Structure.* Ecological Studies 7. Springer, Berlin.

Diadema K., Médail F., Bretagnolle F., 2007. *Fire as a control agent of demographic structure and plant performance of a rare Mediterranean endemic geophytes*. C. R. Biologies 330, 691–700

Dimitrakopoulos A.P., 1993. *Photo-series and fire behaviour prediction based on fuel properties of Mediterranean type ecosystems*. E.U., DG XII, 'ENVIRONMENT' Program, Contract N0. EV5V-CT91-0015, Final Progress Report for the project 'Modeling on forest fires', Chania, Greece.

Dimitrakopoulos A.P., 2002. *Mediterranean Fuel Models and Potential Fire Behavior in Greece*. International Journal of Wildland Fire 11, 127-130.

Elliot K.J., Clinton B.D., 1993. Equations for estimating biomass of herbaceous and woody vegetation in early-successional Southern Appalahian pine-hardwood forest. USDA Forest Service Southeastern Forest Experimental Station Reserch Note SE-365.

Elvidge C.D., 1988. *Thermal infrared reflectance of dry plant materials: 2.5-20.0 micrometers.* Remote Sensing of Environment 26, 265–285.

Erdas Field Guide, 2002

EUFIRELAB, 2007. Deliverable D-02-01 Methods for Wildland Fuel Description and Modelling: A State of the Art

European Civil Protection, 2007. Greece Forest Fires-Summer 2007. http://ec.europa.eu/environment/civil/forestfires_el_2007.htm

European Commission, 2006. *Forest Fires in Europe, 2005*. Official Publication of the European Commission, EUR 22312, EN, European Communities.

Eurostat 1999. *Statistical references*. Luxembourg: Office for official publications of the European Communities, No.2 / 1999.

Eyre F.H., 1980. *Forest cover types of the United States and Canada*. (Society of American Foresters: Washington, D.C.) 147 pp.

Fahnestock G.R., 1970. *Two Keys for Appraising Forest Fire Fuels*. U.S. Forest Service Research Paper PNW-99, 26 pp..

Falkowski M.J., Gessler P.E., Morgan P., Hudak A.T., Smith A.M.S., 2005. *Characterizing and mapping forest fire fuels using ASTER imagery and gradient modeling*. Forest Ecology and Management 217, 129–146.

FAO, Food and Agriculture Organization of the United Nations. 1986. *Wildland Fire management terminology [R]*. For. Pap. M-99.

Fernandes P., Luz A., Loureiro C., Godinho-Ferreira P., Botelho H., 2006. *Fuel modelling and fire hazard assessment based on data from the Portuguese National Forest Inventory*. V International Conference on Forest Fire Research D. X. Viegas (Ed.)

Fernandes P.A.M., 1998. *Fire Spread Modelling in Portuguese Shrubland*. III International Conference on Forest Fire Research, 16-20 November 1998, Vol. II – pp 611 – 628.

Fernandes P.M., 2001. *Fire Spread Prediction in Shrub Fuels in Portugal*. Forest Ecology and Management 144, 67-74.

Fernandes P.M., Rego F.C., 1996. *Changes in fuel structure and fire behaviout with heathland aging in Northen Portugal.* In 13th Fire and Forest Meteorology Conference. Lorne, Australia pp. 433-436. (International Association of Wildland Fire)

Fernandes P.M., Rego F.C., 1998a. *A new method to estimate fuel surface area to volume ratio using water immersion*. International Journal of Wildland Fire 8, 59-66.

Fernandes P.M., Rego F.C., 1998b. *Equations for estimating fuel load in shrub communities dominated by Chamaespatium tridentatum and Erica umbellate.* In III International conference on forest fire research and 14th conference on fire and forest meteorology. Luso, Portugal. (Ed. D.X. Viegas) pp 2553-2564. (ADAI, Univesity of Coimbra, Portugal).

Finney M.A., 1994. *Modeling the Spread and Behaviour of Prescribed Natural Fires*. In Proceedings of the 12th Conference on Fire and Forest Meteorology, pp. 138-143.

Finney M.A., 1998: FARSITE: Fire Area Simulator—model development and evaluation. Research Paper RMRS-RP-4. OGDEN, UT: U.S. Department of Agriculture, Rocky Mountain Research Station. 47 p.

Finney M.A., 2004. FARSITE: Fire Area Simulator-model development and evaluation. Research Paper RMRS-RP-4, Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 47 p..

Finney M.A., 2005. The challenge of quantitative risk analysis for wildland fire. Forest Ecology and Management 211, 97-108

Finney M.A., 2006. *An overview of FlamMap fire modeling capabilities*. In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 2006 28-30 March; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. 213-220.

Finney M.A., 2007. *A computational method for optimizing fuel treatment locations*. International Journal of Wildland Fire 16,702-711.

Fischer W.C., 1981. *Photo guide for appraising downed woody fuels in Montana forests: Interior ponderosa pine, ponderosa pine–larch– Douglas-fir, larch–Douglas-fir, and Interior Douglas-fir cover types*. USDA Forest Service General Technical Report INT-97. 133 pp.

Fischer W.C., Bradley A.F., 1987. *Fire ecology of western Montana forest habitat types*. USDA Forest Service General Technical Report INT- 223. 95 pp.

Flanders D., Hall-beyer M., Pereverzoff J., 2003. Preliminary evaluation of eCognition object-based software for cut block delineation and feature extraction. Canadian Journal of Remote Sensing, 29(4), 441–452.

Fons W., 1950. *Heating and Ignition of Small Woos Cylinders*. Industrial and Engieneering Chemistry 42, 2130-2133.

Fons W.L., 1946. *Analysis of Fire Spread in Light Forest Fuels*. Journal of Agricultural Research 72:93-121.

Forestry Canada Fire Danger Group, 1992. *Development and Structure of the Canadian Forest Fire Behaviour Prediction System*. Canadian Department of Forestry. Inf. Report ST-X-3, 63 pp..

Fosberg M.A., 1970. *Drying rates of heartwood below fiber saturation*. Forest Science 16, 57–63.

Frandsen W.H., 1983. Modelling big sagebrush as a fuel. Journal of Range Management 35(5), 596-600.

Franklin J., Woodcock C.E., 1997. *Multiscale vegetation data for the mountains of southern California: spatial and categorical resolution.* In: Quattrocchi D.A., Goodchild M.F., eds Scale in remote Sensing. Baca Raton, FL: Lewis Publishers: 141-168.

Franklin J.,1995. *Predictive vegetation mapping: geographic modeling of biospatial patterns in relation to environmental gradients.* Progress in Physical Geography 19, 474-499.

Friedl M.A., Michaelsen J., Davis F.W., Walker H., Schimel D.S., 1994. Estimating grassland biomass and leaf area index using ground and satellite data. International Journal of Remote Sensing 15(7), 1401–1420.

Ganis P., 1991. *La diversità specifica nelle comunità ecologiche: concetti, metodi e programmi di calcolo*. Gead-Eq N 10, Trieste

García-Ruiz J.M., Lasanta T., Ruiz-Flano P., Ortigosa L., White S., González C., Martí C., 1996. *Land-use changes and sustainable development in mountain areas: A case study in the Spanish Pyrenees.* Landscape Ecology 11,267-277

Gates D.M., 1980. Biophysical Ecology. Springer Verlag. New York.

Gaudenzio P., Peccenini S., 2002. *Aspetti Vegetazionali della Macchia Mediterranea*. In: Minelli A., Ruffo S., Stoch F. (coord. sc.), 2002. "QUADERNI HABITAT 2002. La Macchia Mediterranea. Formazioni Sempreverdi Costiere". Ministero dell'Ambiente e della Tutela del Territorio. Museo Friulano di Storia Naturale, Comune di Udine.

Giakoumakis N.M., Gitas I.Z., San-Miguel J., 2002. *Object-oriented classification modelling for fuel type mapping in the Mediterranean, using LANDSAT TM and IKONOS imagery: Preliminary results.* In Forest Fire Research and Wildland Fire Safety, pp. 1 – 13, Millpress, Rotterdam, Netherlands.

Gill A.M., Groves R.H., 1981. *Fire regimes in heatlands and their plant-ecological effects*. In Ecosystems of the word, vol9B, Heathland and related shrublands: Analytical studies. (Ed. R.L. Specht) pp. 61-84. (Elsevier: Amsterdam)

Gill A.M., 1975. *Fire and Australian flora: a review*. Australian Forestry 38, 4-25.

Gill A.M., 1981a. *Adaptive responses of Australian vascular plant species to fires. In Fire and the Australian biota*. (Ed. A.M. Gill, Groves R.H., Noble I.R.) pp. 243-272. (Australian Academy of Science: Canberra)

Gill A.M., 1981b. Coping with Fire. In 'The Biology of Australian Plants'. (Eds JS Pate and AJ McComb) pp. 65-87. University of Western Australia: Nedlands

Gill A.M., Bradstock R.A., Williams J.E., 2001. *Fire regimes and biodiversity: legacy and vision.* In Flammable Australia: The fire regimes and biodiversity of a continent. (Eds R.A.Bradstock, Williams J.E, Gill A.M.,) pp 429-446. (Cambridge University Press: Cambridge).

Gleason H.A., 1926. *The individualistic concept of the plant association*. Torrey Botanical Club Bulletin 53, 7-26.

Godinho-Ferreira P., Azevedo A., Reg., F., 2005. *Carta da tipologia florestal de Portugal Continental*. Silva Lusitana 13, 1-34.

Gosz J.R., 1992. *Gradient analysis of ecological change in time and space: Implications for forest management.* Ecological Applications 2(3), 248–261.

Greig-Smith P.,1964. Quantitative plant ecology. London, Butterworths

Grossman D.H., Faber-Langendoen D., Weakley A.S., Anderson M., Bourgeron P., Crawford R., Goodin K., Landaal S., Metzler K., Patterson K.D., Pyne M., Reid M., and Sneddon L., 1998. *International classification of ecological communities: terrestrial vegetation of the United States*. Volume I, The National Vegetation Classification System: development, status, and applications. The Nature Conservancy: Arlington, VA.

Habeck J.R., 1985. *Impact of fire suppression on forest successions and fuel accumulations in long fire interval wilderness habitat type*. In Lotan J.E. et al. tech. cords., Proceedings Symposium and workshop on Wilderness Fires. USDA Forest Service, Intermountain Forest and Range Experimental Station General Technical Report-INT-GTR-182.

Harmon M. E., Sexton J., 1996. *Guidelines for measurements of woody detritus in forest ecosystems*. Publication no. 20. U.S. Long-term Ecological Research (LTER) Network Office, University of Washington, Seattle, Washington, USA.

Harmon M.E., Franklin J.F., Swanson F.J., Sollins P., Gregory S.V., Lattin J.D., Anderson N.H., Cline S.P., Aumen N.G., Sedell J.R., Lienkaemper G.W., Cromack K., Cummins K.W., 1986. *Ecology of coarse woody debris in temperate ecosystems*. Advances in Ecological Research 15, 133–302.

Hessberg P.F., Smith B.G., Kreiter S.G., et al., 1998. *Historical and current forest and range landscapes in the Interior Columbia River Basin and portions of the Klamath and Great Basins.* Part I: Linking vegetation patterns and landscape vulnerability to potential insect and pathogen disturbances. USDA Forest Service General Technical Report PNW-GTR-558. 357 pp.

Hessburg P.F., Salter R.B., Richmond M.B., Smith B.G., 2000. *Ecological subregions in the Interior Columbia River Basin*. USA, Applied Vegetation Science. 3, 163-180.

Hill M.O., 1973. *Diversity and eveness: a unifying notation and its consequences*. Ecology 54, 427-432.

Hornby L.G., 1935. *Fuel type mapping in Region One*. Journal of Forestry 33(1), 67–72.

Hornby L.G., 1936. *Fire control planning in the northern Rocky Mountain region*. Northern Rocky Mountain Forest and Range Experiment Station Progress Report Number 1. Missoula, MT. 180 pp.

Horton J.S., Kraebel C.J., 1955. *Development of vegetation after fire in the chamise chaparral of Southern California*. Ecology, 36: 244-262.

Houghton J.T., Meiro Filho L.G., Callander B.A., Kattenburg A., Maskell K., 1996. *Climate Change 1995.* The Second Assessment Report of the IPCC. Cambridge University Press, Cambridge

http://effis.jrc.ec.europa.eu

http://webhelp.esri.com/arcgisdesktop/9.2

Hutchings S.S., Mason L.R., 1970. *Estimating yields of Gambel oak from foliage cover and basal area.* Journal of Range Management 23,430-434.

ICONA 1990. *Clave fotografica para la identificación de modelos de combustible*. Defensa contra incendios forestales, MAPA, Madrid.

INFC, 2003a. *Guida alla Classificazione della Fegetazione Forestale*. S. Pignatti - Inventario Nazionale delle Foreste e dei Serbatoi Forestali di Carbonio. MiPAF – Direzione Generale per le Risorse Forestali Montane e Idriche, Corpo Forestale dello Stato, CRA-ISAFA, Trento. http://www.isafa.it/scientifica/pubblicazioni/pu_infc/Pubblic.html#FOGLIE

INFC, 2003b. *Manuale di Fotointerpretazione per la classificazione delle Unità di campionamento di prima fase*. Autori: F.De Natale, P. Gasparini - Inventario Nazionale delle Foreste e dei Serbatoi Forestali di Carbonio. MiPAF – Direzione Generale per le Risorse Forestali Montane e Idriche, Corpo Forestale dello Stato, CRA-ISAFA, Trento. http://www.isafa.it/scientifica/pubblicazioni/pu_infc/Pubblic.html#RETIC

INFC, 2003c. *Procedure di Definizione delle Coordinate dei Punti di Campiionamento*. Autori: L. Cavini, G. Scrinzi, A. Floris - Inventario Nazionale delle Foreste e dei Serbatoi Forestali di Carbonio. MiPAF – Direzione Generale per le Risorse Forestali Montane e Idriche, Corpo Forestale dello Stato, CRA-ISAFA, Trento. http://www.isafa.it/scientifica/pubblicazioni/pu_infc/Pubblic.html#COORDIN

INFC, 2003d. *Procedure di Controllo di Qualità dei Dati di Prima Fase.Autori*: A. Cozzi, M. Ferretti - Inventario Nazionale delle Foreste e dei Serbatoi Forestali di Carbonio. MiPAF – Direzione Generale per le Risorse Forestali Montane e Idriche, Corpo Forestale dello Stato, CRA-ISAFA, Trento. http://www.isafa.it/scientifica/pubblicazioni/pu_infc/Pubblic.html#GISWEB

Ivits E., Koch B., Blaschke T., Jochum M., Adler P., 2005. *Landscape structure assessment with image grey-values and object-based classification at three spatial resolutions.* Int. J. Remote Sens., 26, 2975– 2993.

Jemison G.M., Keetch J.J., 1942. *Rate of spread of fire and its resistance to control in the fuel types in eastern mountain forests*. USDA For. Serv., Appalachian Forest Station Techical Note 52. Asheville, N.C.

Jensen J.R., 2005. *Introductory Digital Image Processing*. 3rd Ed., Upper Saddle River, NJ: Prentice Hall, 526 pages.

Jeske B.W., Bevins C.D., 1979. *Spatial and temporal distribution of natural fuels in Glacier Park*. In 'Proceedings of the 1st conference on scientific research in National Parks. Volume II. USDI National Park'. (Ed. RM Linn) Transactions and Proceedings Number 5, pp. 1219–1224.

Keane R.E., Burgan R.A., van Wagtendonk J.B., 2001. *Mapping wildland fuels for fire management across multiple scales: Integrating remote sensing, GIS, and biophysical modeling*. International Journal of Wildland Fire, 10, 301–319.

Keane R.E., Garner J.L., Schmidt K.M., Long D.G, Menakis J.P., Finney M.A., 1998a. *Development of the input data Layers for the FARSITE fire growth model for the Selway–Bitterroot Wilderness Complex*. USA. USDA Forest Service General Technical Report RMRSGTR-3. 121 pp.

Keane R.E., Long D.G., Schmidt K.M., Mincemoyer S., Garner J.L., 1998b. *Mapping fuels for spatial fire simulations using remote sensing and biophysical modeling*. In

'Proceedings of the seventh Forest Service remote sensing applications conference. Nassau Bay, Texas, 6–10 April 1998'. (Ed. JD Greer) pp. 301–316. (American Society for Photogrammetry and Remote Sensing: Bethesda, MD)

Keane R.E., McNicoll C.H., Schmidt K.M., Garner J.L., 1997. *Spatially explicit ecological inventories for ecosystem management planning using gradient modeling and remote sensing.* In 'Proceedings of the sixth Forest Service remote sensing applications conference— Remote sensing; people in partnership with technology'. pp. 135– 146. (American Society of Photogrammetry and Remote Sensing: Bethesda, MD) 448 pp.

Keane R.E., Menakis J.P., Long D., Hann W.J., Bevins C., 1996a. *Simulating coarse scale vegetation dynamics with the Columbia River Basin Succession Model—CRBSUM.* USDA Forest Service General Technical Report INT-340. 50 pp.

Keane R.E., Mincemoyer S.A., Schmidt K.A., Long D.G., Garner J.L., 2000. *Mapping vegetation and fuels for fire management on the Gila National Forest Complex, New Mexico.* USDA Forest Service General Technical Report RMRS-GTR-46-CD.

Keane R.E., Mincemoyer S.A., Schmidt K.M., Long D.G., Garner J.L., 2002. *Mapping vegetation and fuels for fire management on the Gila National Forest Complex, New Mexico.* General Technical Report. RMRSGTR- 46- CD. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. pp. 1-126.

Keane R.E., Morgan P., Running S.W., 1996b*. Fire-BGC—a mechanistic ecological process model for simulating fire succession on coniferous forest landscapes of the Northern Rocky Mountains*. USDA Forest Service Research Paper INT-RP-484. Ogden, UT. 122 pp.

Keeley J.E., 1986. *Resilience of Mediterranean shrub communities to fire, pp. 95-112.* In B. Dell, A.J.M. Hopkins, and B.B. Lamont (eds), Resilience in Mediterranean-type Ecosystems. Dr. W. Junk, Dordrecht, The Netherlands.

Keeley J.E., 2002 *Fire management of California shrubland landscapes*. Environmental Management 29, 395-408

Keeley J.E., Fotheringham C.J., 2002. *Impact of past, present, and future fire regimes on North American Mediterranean shrublands*. In Fire Regimes and climatic changes in temperate and boreal ecosystems of the Western Americans. (Eds. T.W. Swetnam, G. Montenegro and T.T. Veblen) pp. 214-258. (Springer-Verlag: New York)

Keeley S.C., Keeley J.E., Hutchinson S.M., Johnson A.W., 1981. *Postfire succession of herbaceous flora in southern California chaparral*. Ecology 62(6),1608-1621.

Keith D.A., McCaw W.L., Whelan R.J., 2001a. *Fire regimes in Australian heath: a conceptual model and field investigatons.* Journal of Vegetation science 5, 347-354.

Kessell S.R., 1979. *Gradient modeling: resource and fire management*. Springer-Verlag: New York, 432 pp.

Ketting R.L., Landgrebe D.A., 1976. *Classification of multispectral image data by extraction and classification of homogeneous objects*. IEEE Transactions on Geoscience Electronics. vGE-14 i1. 19-26.

King A.R., and Linton M., 1963. *Moisture variation in forest fuels: the rates of responses to climate changes.* Australian Journal of applied science 14, 38-49

King N.K., 1973. *The influence of water vapour on the emission spectra of flames*. Combustion Sciences and Technology 6, 247-256.

Knight D.H., Loucks O.L., 1969. *A quantitative analysis of Wisconsin forest vegetation on the basis of plant function and gross morphology*. Ecology 50, 219-234.

Komarek E.V., 1967. *The nature of lightning fire.* In Tall Timbers fire Ecology Conference. Proceedings 7, 5-41.

Köppen W., 1923. *Die Klimate der Erde*. De Gruyter.

Kourtz P.H., 1977. *An application of Landsat digital technology to forest fire fuel mapping*. In 'Fire ecology in resource management: A workshop'. (Ed. DE Dube) pp. 79–81. Northern Forest Research Centre: Edmonton, Alberta. Information Report NOR-X-21.

Kuchler A.W., 1967. *Vegetation Mapping*. Ronald Press

Lachowski H., Maus P., Golden M., Johnson J., Landrum V., Powell J., Varner V., Wirth T., Gonzales J.S., Bain S., 1995. *Guidelines for the use of digital imagery for vegetation mapping.* USDA Forest Service Engineering Staff EM-7140-25. 168 pp.

Laliberte A.S., Rango A., Havstad K.M., Paris J.F., Beck R.F., McNeely R., Gonzalez A.L., 2004. *Object-oriented image analysis for mapping shrub encroachment from 1937 to 2003 in southern NewMexico*. Remote Sensing Environment., 93, 198– 210.

Lancaster J.W., 1970. *Timelag useful in fire danger rating*. Fire Control Notes 31(3),6–8.

Lasaponara R., Lanorte A., 2006. *Multispectral fuel type characterization based on remote sensing data and Prometheus model*. Forest Ecology and Management 234S, S226.

Lasaponara R., Lanorte A., 2007a. *On the capability of satellite VHR QuickBird data for fuel type characterization in fragmented landscape*. Ecological Modelling 204, 79–84.

Lasaponara R., Lanorte A., 2007b. *Remotely sensed characterization of forest fuel types by using satellite ASTER data.* International Journal of Applied Earth Observation and Geoinformation 9, 225–234.

Le Houérou H.N., 1993. *Land degradation in Mediterranean Europe: can agroforestry be a part of the solution?* A prospective review. Agrofor Sys 21, 43-61.

Lee H.C., 1941. *Aerial photography: a method for fuel type mapping*. Journal of Forestry 39, 531–533.

Leenhouts B., 1998. Assessment of biomass burning in the conterminous United States. Conservation Ecology [online] 2(1):1 Available from the Internet. URL: http://www.consecol.org/vol2/iss1/art1.

Leone V., Saracino A., De Natale F., 1993. *I Modelli di Combustibile e la Previsione del Comportamento del Fuoco*. In: Cellulosa e Carta n. 2.

Loveland T.R., Merchant J.W., Ohlen D.O., Brown J.F., 1991. *Development of a land-cover characteristics database for the conterminous U.S.* Photogrammetric Engineering and Remote Sensing 57(11), 1453–1463.

Loveland T.R., Ohlen D.O., Brown J.F., Reed B.C., Merchant J.W., 1993. *Prototype 1990 conterminous United States land cover characteristics data set CD-ROM.* EROS Data Center, US Geological Survey CD-ROM 9307. 1 disk.

Lund H.G., 1969. *Appraising and mapping fuels with aerial photographs*. Report No. Proceedings American Society of Photogrammetry and American Congress on Surveying and Mapping. American Society of Photogrammetry, Portland, OR.

Lunetta R.S., Lyon J.G., Guindon B., Elvidge C.D., 1998. *North American landscape characterization dataset development and data fusion issues.* Photogrammetric Engineering and Remote Sensing 64(8), 821–829.

Lutes D.C., 1999. *Assessment of the Line Transect Method: An Examination of the Spatial Patterns of Down and Standing Dead Wood*. In Symposium on the Ecology and Management of Dead Wood in Western Forests, November 2-4, 1999, Reno, Nevada.

Lutes D.C., 2002. *Assessment of the Line Transect Method: An Examination of the Spatial Patterns of Down and Standing Dead Wood*. In: W. F. Laudenslayer, Jr., Shea, P. J., Valentive, B. E., Weatherspoon, C. P., Lisle, T. E., editor. Proceedings of the symposium on the ecology and management of dead wood in western forests. 1999, Nov. 2-4, Reno, NV. General Technical Report PSW-GTR-181. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA. 665-675.

Lutes D.C., Keane R.E., Caratti J.F., Key C.H.,Benson N.C., Sutherland S., Gangi L.J., 2006. FIREMON: Fire effects monitoring and inventory system. General Technical. Report RMRS-GTR-164-CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Lutes D.C., Keane R.E., Caratti J.F., Key C.H.,Benson N.C., Sutherland S., Gangi L.J., 2006. *FIREMON: Fire effects monitoring and inventory system*. General Technical.

Report RMRS-GTR-164-CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Lutes, Duncan C. 2002. *Assessment of the Line Transect Method: An Examination of the Spatial Patterns of Down and Standing Dead Wood.* In: W. F. Laudenslayer, Jr., Shea, P. J., Valentive, B. E., Weatherspoon, C. P., Lisle, T. E., editor. Proceedings of the symposium on the ecology and management of dead wood in western forests. 1999, Nov. 2-4, Reno, NV. General Technical Report PSW-GTR-181. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA. 665-675.

Lyon J., 1968. *Estimating twig prodution of serviceberry from rown volumes*. Journal of Wildlife management 32(1), 115-119.

Maheras P., 1988. *Changes in precipitation conditions in the western Mediterranean over the last century*. Journal of Climatology 8, 179-189

Margalef R., 1960. *Ideas for a synthetic approach to the ecology of running waters*. Int Rev Ges Hydrobiol 45:133–153

Margaris N.S., 1980. *Structure and dynamics of Mediterranean-type vegetation*. Portugaliae Acta Biologica 16: 45-58.

Marsden-Smadley J.B., Catchpole W.R., 1995a. *Fire behaviour modelling in Tasmanian buttongrass moorlands.* I. Fuel characteristics. International Journal of Wildland Fire 5, 203-214.

Marsden-Smadley J.B., Catchpole W.R., 1995b. *Fire behaviourmodelling in Tasmanian buttongrass moorlands.* II. Fire behaviourbehaviour . International Journal of Wildland Fire 5,215-228.

Marsden-Smedley J.B., 1998. *Changes in the fire regime of southwest Tasmania over the last 200 years*. Papers and Proceedings of the Royal Society of Tasmania, 132, pgs. 15-29

Martin R.E., Anderson H.E., Boyer W.D., Dieterich J.H., Hirsch S.N., Johnson V.J., McNab W.H., 1979. *Effects of Fire on Fuels: A State of Knowledge review.* USDA Forest Service, General Technical Report WO-13.

Maselli F., Rodolfi A, Bottai L., Conese C., 1996. *Evaluation of forest fire risk by the analysis of environmental data and TM images*. International Journal of Remote Sensing 17(7), 1417–1423.

Maselli F., Rodolfi A., Bottai S., Romanelli S., Conese C., 2000. *Classification of Mediterranean vegetation by TM and ancillary data for the evaluation of fire risk*. International Journal of Remote Sensing. 17, 3303– 3313.

Mausel P.W., Kalaluka G.Y., Lee J.K., Mudderman D.E., Escobar D.E., and Davis. M.R., 1990. *Multispectral video analysis of micro-relief dominated poorly drained soils in western Indiana.* J.Imaging Technology 16, 113-119.

Maxwell W.G.,Ward F.R., 1976a. *Photo series for quantifying forest residues in the: coastal Douglas-fir-hemlock type, coastal Douglas-fir-hardwood type.* General Technical. Report PNW-51. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 103 p.

Maxwell W.G.,Ward F.R., 1976b. *Photo series for quantifying forest residues in the: ponderosa pine type, ponderosa pine and associated species type.* General Technical Report PNW-52. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 73 p.

Mazzoleni S., 1989. *Fire and Mediterranean plants: germination responses to heat exposure*. Annals of Botany 47: 227-233.

McArthur A.G., 1966. *Weather and Grassland Fire Behaviour*. Forest Research Institute, Forest and Timber Bureau of Australia. Leaflet No. 100.

McArthur A.G., 1997. *Grassland fire danger meter mark 5*. Country Fire Authority, Melbourne, Victoria.

McCarthy G., 1998. *Assessment of overall fuel hazard for a site and its implications for both strategic fuel management and first attack success probability*. Pp. 79 In Proc. 13th Conf. on Fire and Forest Meteorology, Oct. 1996, Lorne, Melbourne, Australia. International Association of Wildland Fire.

McCaw W.L., 1991a. *Fire spread prediction in mallee-heat shrubland in south-western Australia.* In 11th International conference on fire and forest meteorology. Missoula, Montana, USA. (eds Andrews P.L. and D.F. Potts) pp 226-233. (Society of American Foresters)

McCaw W.L., 1991b. *Measurement of fuel quantity and structure for bushfire research and management.* In Conference on bushfire modeling and fire danger rating systems. Canberra. (eds. N.P. Cheney and A.M. Gill) pp. 147-156. (CSIRO)

McCaw W.L., 1995. *Predicting fire spread in Western Australian mallee-heath*. CALMScience Supplement 4, 35-42.

McCaw W.L., 1997. *Predicting fire spread in Western Australian mallee-heat shrubland.* PhD thesis, School of Mathematics and Statistics, university of New South Wales (Australian Defence Force Academy).

McKinley R.A., Chine E.P., Werth L.F., 1985. *Operational fire fuels mapping with NOAA-AVHRR data.* Pecora X symposium proceedings, pp. 295–304. (American Society for Photogrammetry and Remote Sensing: Falls Church, VA)

Menakis J.P., Keane R.E., Long D.G., 2001. *Mapping ecological attributes using an integrated vegetation classification approach.* Journal of Sustainable Forestry 11 (1/2), 245–265.

Merrill D.F., Alexander, M.E., 1987. *Glossary of forest fire management terms.* National Research Council of Canada, Committee for Forest Fire Management, Ottawa.

Miller W., Johnston D., 1985. *Comparison of fire fuel maps produced using MSS and AVHRR data.* Pecora X symposium, pp. 305–314. (American Society for Photogrammetry and Remote Sensing: Falls Church, VA)

Mooney H.A., 1977*. Southern coastal scrub.* Pages 471-489 In M. G. Barbour and J. Major, eds. Terrestrial vegetation of California. John Wiley and Sons, New York.

Moreno J.M., Oechel W.C., 1992. *Factors controlling post-fire seedling establishment in southern California.* Chaparral. Oecologia 90, 50-60.

Moreno J.M., Vázquez A., Vélez R., 1998. *Recent history of forest fires in Spain.* In: Moreno JM (ed) Large Fires. Backhuys Publishers, Leiden, The Netherlands, pp 159-185

Moritz M.A., 2003. *Spatio-temporal analysis of controls of shrubland fire regimes: Age dependency and fire hazard.* Ecology 27, 433-441.

Moro C, 1997. *DETERMINATION DES CARACTERISTIQUES PHYSIQUES DE PARTICULES DE QUELQUES ESPECES FORESTIERES MEDITERRANEENNES.* Institut National de la Recherche Agronomique Département Ecologie des Forêts, Prairies et milieux Aquatiques Unité de Recherches Forestières Méditerranéennes Equipe de Prévention des Incendies de Forêt Document PIF2006-06

Morris W.G., 1970. *Photo inventory of fine logging slash.* Photogrammetric Eng. 36, 1252–1256.

Mueller-Dombois D., Ellenberg H., 2003. *Aims and Methods of Vegetation.* The Blackburn Press.

Muraro S.J., 1970. *Slash Fuel Inventories from 70mm Low-level Photography.* Canadian Forest Service, Ottawa, Ontario, p. 63.

National Wildfire Coordinating Group, 1996. National Interagency Fire Center, Attn: Supply, 3833 S. Development Avenue, Boise, ID 83705; http://www.nwcg.gov/pms/pubs/catalog.htm

Naveh Z., 1973 *The ecology of fire in Israel.*In Proceedings Tall Timber Fire Ecology Conference 13, 131–170. Tallahassee, Florida.

Naveh Z., 1975. *The Evolutionary Significance of Fire in the Mediterranean Region.* Vegetatio 29: 199-208.

Nelson R.M., 2001. *Water relations of forest fuels*. In Forest fires: Behavior and ecological effects. (Eds EA Johnson and K Miyanishi) pp. 79-150. Academic Press: San Diego, USA.

Nixon S.W., 1995. *Coastal marine eutrophication: a definition, social causes, and future concerns*. Ophelia 41,199-219

Oakley K. P. 1961. *On man's use of fire, with comments on toolmaking and hunting*. Viking Fund Publ. Anthropol. 31,176-193.

O'Hara K., Latham P., Hessburg P., Smith B., 1996. *Development of a forest stand structural stage classification for the Interior Columbia River Basin.* Western Journal of Applied Forestry 11(3), 97–102.

Ohlen D.O., Despain D.G., Burgan R.E., 2000. National vegetation Mapping for fire applications. Proceedings from The Joint Fire Science Conference and Workshop, "Crossing the Millennium Integrating Spatial Technologies and Ecological Principles for New Age in Fire management, Boise, ID, p. 205-211.

Ohmann J.L., 1996. *Linking plot data, models and maps in regional ecological analysis*. In Proceedings of the 1995 Society of American Foresters convention; 1995 October 12 November 1; Portland, ME, SAF 96-01. Bethesda, MD; Society of American Foresters: 99-103.

Ohmann J.L., Spies T.A., 1998. *Regional gradient analysis and spatial pattern of woody plant communities of Oregon forests.* Ecological Monographs 68(2), 151–182.

Oliver C.D., Larson B.C., 1996. *Forest Stand Dynamics*. John Wiley & Sons, New York 520 pp.

Omernik J.M., 1987. *Ecoregions of the conterminous United States*. Annals of the Association of American Geographers 77(1), 118–125.

Oswald B.P., Fancher J.T., Kulhavy D.L., Reeves H.C., 1999. *Classifying fuels with Aerial Photography in East Texas*. Int. J. Wildland Fire 9 (2), 301–319.

Ottmar R.D., Sandberg D.V., Riccardi C.L., Prichard S.J. 2007. *An overview of the Fuel Characteristic Classification System-Quantifying. classifying, and creating fuelbeds for resource planners.* Canadian Journal of Forestry Research, 37

Ottmar R.D., Vihnanek R., Alvarado E., 1994. *Forest health assessment: Air quality tradeoffs.* In 'Proceedings of the 12th international conference on fire and forest Meteorology, 26–28 October 1993, Jekyll Island, Georgia'. pp. 47–62. (Society of American Foresters: Bethesda, MD)

Ottmar R.D., Vihnanek R.E., 1998. *Stereo photo series for quantifying natural fuels*. Vol. II. Black spruce and white spruce types in Alaska. National Wildland Coordinating Group, National Interagency Fire Center, Boise, Idaho. PMS 831.

Ottmar R.D., Vihnanek R.E., 1999. *Stereo photo series for quantifying natural fuels. Volume V: Midwest red and white pine, Northern tallgrass prairie, and mixed oak types in the Central and Lake States.* PMS 834. Boise, ID: National Wildfire Coordinating Group, National Interagency Fire Center. 99 p.

Ottmar R.D., Vihnanek R.E., 2000. *Stereo photo series for quantifying natural fuels. Volume VI: longleaf pine, pocosin, and marshgrass types in the Southeast United States.* PMS 835. Boise, ID: National Wildfire Coordinating Group, National Interagency Fire Center. 56 p.

Ottmar R.D., Vihnanek R.E., 2002. *Stereo photo series for quantifying natural fuels. Volume IIa: hardwoods with spruce in Alaska.* PMS 836. Boise, ID: National Wildfire Coordinating Group, National Interagency Fire Center. 41 p.

Ottmar R.D., Vihnanek R.E., Wright C.S., Olson D.L., 2004. *Stereo photo series for quantifying natural fuels.* Volume VII. Oregon white oak, California deciduous oak, and mixed-conifer with shrub types in the Western United States. National Wildfire Coordinating Group, National Interagency Fire Center, Boise, Idaho. PMS 839.

Pala S., Taylor D., Holder G., 1990. *Integrating satellite-derived forest fuel data into fire management decision support models.* Proceedings, 2nd National GIS conference, Ottawa, 5–8 March

Pala. S., Taylor D., 1989. *The foundation for province-wide forest fuel mapping*. Proceedings, 12th Canadian symposium on remote sensing, Vancouver, B.C., July

Papiò C., Trabaud L., 1991. *Comparative sudy of the aerial structure of five shrubs of Mediterranean shrublands.* Forest Science 37, 146-159.

Pattern D.T., 1963. *Vegetation pattern in relation to environments in the Madison range, Montana.* Ecological Monigraphs. 34, 374-406.

Pausas J.G., 1999*. Mediterranean vegetation dynamics: modelling problems and functional types.* Plant Ecology 140, 27-39

Pausas J.G., Vallejo R.V., 1999*. The role of fire in European Mediterranean Ecosystems.* In: Chuvieco E. (ed.) Remote sensing of large wildfires in the EuropeanMediterranean basin, pp.3-16. Springer-Verlag.

Pellizzaro G., Ventura A., Zara P., 2005*. Influence of Seasonal Weather Variations on Fuel Status for some Shrubs Typical of Mediterranean Basin*. In: Proceedings of the 6th Fire and Forest Meteorology Symposium; 2005, October 25-27, Canmore, AB, Canada.

Pereira J.M.C., Sequeira M.S., Carreiras J.M.B., 1995. *Structural properties and dimensional relations of some Mediterranean shrub fuels.* International Journal of Wildland Fire 5, 35-42.

Peressotti A., Magliulo E., 1999. *Traspirazione e flusso di linfa xilematica in un ecosistema mediterraneo: confronto tra specie mediante trasduttori di flusso di linfa a bilancio termico ed eddy covariance.* In Monitoraggio di un sistema a macchia mediterranean: misure eco fisiologiche e micro meteorologiche. Eds Benincasa F., Cristoferi G., Maracchi G., Tedeschi P. Collana tecnico-scientifica INAPA, Quaderno n.6.

Pfister R.D., Kovalchik B.L., Arno S.F., Presby R.C., 1977. *Forest habitat types of Montana.* USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report INT-34. Ogden, UT. 174 pp..

Philpot C.W., 1968. *Mineral content and pyrolysis of selected plant material.* USDA Forest Service. Intermountain Forest and Range Experimental Station Research Note INT-84, 4 p.

Pignatti S., 1995 - *Ecologia vegetale*: Ecologia del fuoco di Manuela De Lillis Le successioni di Sandro Pignatti UTET Edit.

Piñol J., Terradas J., 1996. *Els incendis forestals al litoral mediterrani catalano-valencià en el període 1968-1995.* Butlletí del Centre d'Estudis Selvatans 4,69-96

Piñol J., Terradas J., Lloret F., 1998. *Climatic warming hazard, and wildfire occurrence in coastal eastern Spain.* Climatic Change 38, 345-357

Pisanu P.A., 2005. *Calibrazione e Validazione di un nuovo Indice di Previsione del Pericolo di Incendi Boschivi.* Tesi di Dottorato, Università degli Studi di Sassari, Facoltà di Agraria, Dipartimento di Economia e Sistemi Arborei, 159 pp.

Plucinsky M.P., 2003. *The investigation of factors governing ignition and development of fires in heathland vegetation.* PhD Thesis. University of New South Wales - Australian Defence Force Academy

Prescription for the Forest Police, September 2006. ASSESSORATO DELLA DIFESA DELL'AMBIENTE PRESCRIZIONI DI MASSIMA E DI POLIZIA FORESTALE PER I BOSCHI E TERRENI SOTTOPOSTI A VINCOLO IDROGEOLOGICO POR SARDEGNA 2000/2006 ASSE IV MISURA 4.7. BOLLETTINO UFFICIALE n. 29 del 7 settembre 2006

Prometheus Project, 1999. *Management Techniques for optimization of suppression and minimization of wildfire effects.* System Validation. European Commission, contract number ENV4-CT98-0716.

Pyne S.J., Andrews P.L., Laven A.R., 1996. *Introduction to Wildfire – 2nd Edition.* John Wiley and Sons Edition. New York. 769 pp..

Quigley T.M., Graham R.T., Haynes R.W., 1996. *An integrated scientific assessment for ecosystem management in the Interior Columbia River Basin and portions of the*

Klamath and Great Basins. USDA Forest Service, Pacific Northwest Research Station General Technical Report PNW-GTR-382. Portland OR. 126 pp.

Ramensky L.G., 1930. *Zur Metodik der vergleichenden Beabeitung und Ordnungg von Pflanzenlisten und anderen obJekten, die durch mehrere verschiedenartig wirkenende Faktoren bestimmt werden.* Beitr. Biol. Pflanz. 18, 269-304.

Redmond R.L., Prather M.L., 1996. *Mapping existing vegetation and land cover across western Montana and north Idaho*. Report on file at: USDA Forest Service, Northern Region, Ecosystem Management. PO Box 7669, Missoula, MT. Contract 53-0343-4-000012. 211 pp.

Rego F.C., 1992. *Land use changes and wildfires*. In: Teller, A., Mathy, P., Jeffers, J. (Eds.), Response of Forest Ecosystems to Environmental Changes. Elsevier, London, pp. 367–373.

Rego F.C., Pereira J., Fernandes P., Almeida A., 1994. *Biomass and aerial structure characteristics of some Mediterranean shrub species*. In Proceedings 2nd International Conference on Forest Fire Research. 21-24 November. Coimbra.

Rego F.C., Pereira J., Fernandes P., Almeida A., 1994. *Biomass and aerial structure characteristics of some Mediterranean shrub species*. In Proceedings 2nd International Conference on Forest Fire Research. 21-24 November. Coimbra.

Reid A., Shone D.L., Akujor C.E., Browne I.W.A., Murphy D.W., Pedelty J., Rudnick L., Walsh D., 1995. *High resolution radio maps of quasars from the Jodrell Bank 966MHz survey.* Astronomy and Astrophysics Supplement, v.110, p.213

Reinhart K.O., Menges E.S., 2004. *Effects of re-introducing fire to a central Florida sandhill community.* Applied Vegetation Science 7, 141-150

Riaño D., Chuvieco E., 2002. *Generation of fuel type maps from Landsat-TM images and auxiliary data in Mediterranean ecosystem.* Alcalà de Henares, Spain, Department of Geography, Alcalà de Henares University.

Riccardi C.L., Andreu A.G., Elman E., Kopper K., Long J., Ottmar R.D., 2006. *A national system to characterize physical properties of wildland fuels*. Canadian Journal of Forestry Research, 37

Riccardi C.L., Ottmar R.D., Sandberd D.V., Andreu A.G., Elman E., Kopper K., Long J., 2007a. *The fuel bed: a key element of the Fuel Charecteristics Classification System*. Canadian Journal of Forestry Research, 37

Riccardi C.L., Prichard S.J., Ottmar R.D., Sandberd D.V., 2007b. *Quantifying physical characteristics of wildland fuels in the Fuel Characteristic Classification System.* Canadian Journal of Forestry Research, 37

Rice E.L., 1967. A statistical method for determining quadrat size and adequacy of sampling. Ecology. 48, 1047-1049.

Roberts D., Gardner M., Regelbrugge J., Pedreros D., Ustin S., 1998. *Mapping the distribution of wildfire fuels using AVIRIS in the Santa Monica Mountains Available* online:In: http:// www.cstars.ucdavis.edu/papers/html/robertsetal1998c/ index.html.

Roberts D.A., Green R.O., Adams J.B., 1997. *Temporal and spatial patterns in vegetation and atmospheric properties from AVIRIS.* Remote Sens. Environ. 62: 223–240.

Rollins M.G., 2000. *Twentieth century fire patterns in the Gila/Aldo Leopold Wilderness Areas, New Mexico and the Selway–Bitterroot Wilderness Area in Idaho/Montana.* Ph.D. Dissertation. On file at the Laboratory of Tree-Ring Research, The University of Arizona, Tucson, AZ. 184 pp.

Rollins M.G., Frame C.K., 2006. The LANDFIRE Prototype Project: nationally consistent and locally relevant geospatial data for wildland fire management. Gen. Tech. Rep. RMRS-GTR-175.. U.S. Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado.

Rollins M.G., Keane R.E., Parson R.A., 2004. *Mapping fuels and fire regimes using remote sensing, ecosystem simulation, and gradient modeling.* Ecological Applications, 14(1), pp. 75–95

Romme W.H., Knight D.H., 1981. *Fire frequency and subalpine forest succession along a topographic gradient in Wyoming.* Ecology 62, 319-326.

Root R.R., Stitt S.C.F., Nyquist M.O., Waggoner G.S., Agee J.K., 1985. *Vegetation and fire fuel models mapping of North Cascades National Park.* ACSM-ASPRS Annual Convention Technical Paper 3, 78–85.

Root R.R., van Wagtendonk J.W., 1999. *Hyperspectral analysis of multi-temporal Landsat TM data for mapping fuels in Yosemite National Park.* In 'Annual ASPRS Conference, Portland, OR, 17-21 May 1999'. (Society of American Photogrammeters: Bethesda, MD) pp. 399–408.

Rothermel R.C., 1972. *A Mathematical Model for Predicting Fire Spread in Wildland Fuels.* USDA Forest Service Research Paper, INT-115. Ogden, UT: Intermountain Forest and Range Experiment Station.

Rothermel R.C., Anderson H.E., 1966. *Fire spread characteristics determined in the laboratory.* USDA Forest Service, Intermountain Research Station, research Paper, INT-30, Odgen, Utah, USA.

Rothermel R.C., Philpot C.W., 1973. *Predicting changes in chaparral flammability.* Journal of Forestry 71, 640-643.

Roxo M.J., Cortesao Casimiro P., Soeiro de Brito R., 1996. *Inner Lower Alentejo field site: Cereal cropping, soil degradation and desertification.* In: Brandt CJ, Thornes J (eds) Mediterranean desertification and land use. J Wiley & Sons, Chichester, pp.111-135

Running S.W., Nemani R.R., Peterson D.L., Band L.E., Potts D.F., Pierce L.L., Spanner M.A., 1989. *Mapping regional forest evapotranspiration and photosynthesis by coupling satellite data with ecosystem simulation*. Ecology 70(4), 1090–1101.

Ryan K.C., Johnson R.E., 2006. Stereo Photographs aid residue management. Fire management Today. Available on line

Saglam B., Kucuk O., Bilgili E., Dinç Durmaz B., Baysal I., 2008. *Estimating Fuel Biomass of Some Shrub Species (Maquis) in Turkey.* Turk J Agric For

Sala M., Rubio J.L. (eds), 1994. *Soil erosion and degradation as a consequence of forest fires*. Geforma Ediciones, Logroño

Salas F.J., Chuvieco E., 1995. *Aplicacion de imagenes Landsat-TM a la cartografia de modelos de combustible*. Revista de Teledeteccion 5, 18–28.

Salas J., Chuvieco E., 1994. *Geographic information system for wildland fire risk mapping*. Wildfire 3, 7–13.

Salis M., 2008. *Fire Behaviour Simulation in Mediterranean Maquis Using FARSITE (FIRE AREA SIMULATOR)*. PhD. Thesis. Università degli Studi di Sassari, Dipartimento di Economia e Sistemi Arborei, 130 pp..

Sandberg D.V., Ottmar R.D., Cushon G.H., 2001. *Characterizing fuels in the 21st Century*. International Journal of Wildland Fire 10, 381–387.

Sandberg D.V., Riccardi C.L., Schaaf M.D., 2007a. *Fire potential rating for wildland fuelbeds using the Fuel Characteristic Classification System*. Can. J. For. Res. 37.

Sandberg D.V., Riccardi C.L., Schaaf M.D., 2007b. *Reformulation of Rothermel's wildland fire behaviour model for heterogeneous fuelbeds*. Can. J. For. Res. 37.

Sawaya K.E., Olmanson L.G., Heinert N.J., Brezonik P.L., Bauer M.E., 2003. *Extending satellite remote sensing to local scales: land and water resource monitoring using high-resolution imagery.* Remote Sensing of Environment 88, 144–156.

Schaaf M.D.. Sandberg D.V., Schreuder M.D., Riccardi C.L., 2007. *A conceptual framework for ranking crown fire potential in wildland fuelbeds*. Canadian Journal of Forest Research 37.

Scott J.H., Burgan R.E., 2005. *Standard Fire Behaviour Fuel Models: a Comprehensive Set for Use with Rothermel's Surface Fire Spread Model*. General Tech. Report RMRS-GTR-153. Fort Collins, CO: USDA, Forest Service, Rocky Mountain Research Station. 72 p..

Scott K., Oswald B., Farrish K., Unger D., 2002. *Fuel loading prediction models developed from aerial photographs of the Sangre de Cristo and Jemez mountains of New Mexico, USA*. International Journal of Wildland Fire 11, 85–90.

Sebastian-Lopez A., San Miguel-Ayanz J., Libertà G., 2000. An integrated forest fire risk index for Europe. 20th Earsel Symp. Dresden.

Sebastifin-Lopez A., San Miguel-Ayanz J., 2002. *Integration of satellite sensor data, fuel type maps and meteorological observations for evaluation of forest fire risk at the pan-European scale.* International Journal of Remote Sensing 23, 2713-2719.

Shannon C.E, 1948. *A mathematical theory of communication*. Bell System Technical Journal 27, 379–423 and 623–65.

Shasby M.B., Burgan R.E., Johnson R.R., 1981. *Broad area forest fuels and topography mapping using digital Landsat and terrain data.* In 'Proceedings of the 7th international symposium on machine processing of remotely sensed data, West LaFayette, LO'. pp. 529–537

Shea S.R., McCormick J., Portlock C.C., 1979. The effect of fires on regeneration of leguminous species in the northern Jarrah (Eucalyptus marginata Sm.) forests of Western Australia,'Australian Journal of Ecology vol. 4, pp. 195-205.

Show S.B., Kotok E.I., 1929. *Cover type and fire control in the national forests of northern California*. Report No. 1495. USDA, Forest Services, Washington, DC.

Show S.B., Kotok E.I., 1930. *The determination of hour control for adequate fire protection in the major cover types of the California pine region.* USDA, Agriculture Technical Bulletin No. 209.

Sirca C., Spano D., Duce P., Pisanu P., 2005. *ICHNUSA Fire Index: Development and Preliminary Evaluation at Regional Scale*. 6th Symposium on Fire and Forest Meteorology/19th interior West Fire Council Meeting. Canmore, Alberta, Canada, 25-27 October 2005.

Spano D., Georgiadis T., Duce P., Rossi F., Delitala A., Dessy C., Bianco G., 2005. *A Fire Index for Mediterranean Vegetation based on Micrometeorological and Ecophysiological Measurements*. Fifth Symposium on Fire and Forest Meteorology-American Meteorological Society, Orlando (USA).

Specht R.L., 1970. Vegetation. In The Australian environment. Eds G.W. Leeper, pp 44-67. CSIRO- Melbourne University Press: Melbourne.

Stahl G., Ringvall A., Lamas T., 2000. Guided transect sampling for assessing sparse populations. Forestry Science 46, 108-115.

Stewart O.C., 1956. Fire as the first great force employed by man. In: Man's role in changing the face of the earth, ed. W. I. Thomas, pp, 115-133, Univ. of Chicago.

Stocks B.J., 1970. *Moisture in the forest floor – its distribution and movement.* Canada Department of Fisheries and Forestry, Publication 1271. Canadian Forestry Service: Ottawa, ON

Stockstad D. S., 1967. *Ignition properties of fine forest fuels*. USDA Forest Service Intermountain Forerest and Range Experiment Station, Ogden, Utah.

Stow D., Hope A., McKinsey D., Pray H., 1993. *Deriving dynamic information on fire fuel distributions in southern Californian chaparral from remotely sensed data.* Landscape and Urban Planning 24, 113–127.

Stratton R. D., 2004. *Assessing the effectiveness of landscape fuel treatments on fire growth and behavior.* Journal of Forestry 102(7), 32– 40.

Stratton R., 2006. *Guidance on spatial wildland fire analysis: models, tools, and techniques*. Gen. Tech. Rep. RMRS-GTR-183. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 15 p.

Susmel L., 1973. *Swiluppi e problemi attuali del controllo degli incendi nella foresta mediterranean.* FAO, Rome.

Susott R.A., 1982. *Differential scanning calorimetry of forest fuels*. Forestry Sciences 28, 839-851.

Takahashi M., Kikuchi T.,. 1986. *The heat effect on seed germination of some species in the initial stage of a post-fire vegetation.* Ecological Review. 21(1): 11-14.

Tansley A.G., Chipp T.F., 1926. (EDS.) *Aims & Methods in the Study of Vegetation London* Bit.Emp.Veg.Comm. ill.w/62 fig., 383pp.

Thanos C.A., Georghiou K., Kadis C.C., Pantazi C., 1992. *Cistaceae: A plant family with hard seeds.* Israel Journal of Botany 41, 251-263

Thompson S. K., 1992. *Sampling*. John Wiley & Sons, Inc., New York, NY.

Tian X., McRae D.J., Shu L., Wang M., 2005. *Fuel classification and mapping from satellite imagines*. Journal of Forestry Research, 16, 311-316.

Trabaud L., 1974. *Experimental study of the effects of prescribed burning on a Quercus coccifera* L. Garrigue. Proc. Annu. Tall Timbers Fire Ecol. Conf. 13: 97-129.

Trabaud L., 1977. *Comparison between the effect of prescribed fires and wild fires on the global quantitative development of the kermes scrub oak (Quercus coccifera L) garrigues*. Symp. Environm. Consequences Fire and Fuel Manage. Medit. Ecosystems. U.S. For. Serv. General Tech. Report WO 3, 27••282.

Trabaud L., 1977. *Comparison between the effect of prescribed fires and wild fires on the global quantitative development of the kermes scrub oak (Quercus coccifera L) garrigues.* Symp. Environm. Consequences Fire and Fuel Manage. Medit. Ecosystems. U.S. For. Serv. General Tech. Report WO 3, 27••282.

Tryon R.C., 1939. *Cluster Analysis*. Edwards Brothers

U.S. Department of Agriculture, Forest Service, 1964. *Handbook on National Fire-Danger Rating System*. USDA For. Serv. Handb. FSH 5109.11. Washington, D.C.

UNESCO 1963, Bioclimatic map of the mediterranean zone. Explanatory notes. Arid Zone Research 21; Paris, France; UNESCO.

USDA Forest Service, 1974. *National fuel classification and inventory system*. Preliminary draft. Washington, DC: USDA Forest Service, Washington Office.

USDA Forest Service. 1968. *Guide for fuel type identification*. Portland, OR: USDA Forest Service, Pacific Northwest Region.

Usò J.L., Mateu J., Karjalainen T., Salvador P, 1997. *Allometric regression equations to determine aerial biomasses of Mediterranean shrubs*. Plant Ecology 132: 59–69.

Van der Sande C.J., de Jong S.M., de Roo A.P.J., 2003. *A segmentation and classification approach of IKONOS-2 imagery for land cover mapping to assist flood risk and flood damage assessment.* International Journal of Applied Earth Observation and Geoinformation 4, 217–229.

Van Hees W.W.S., Dobelbower K., Winterberg K., 2001. *Forest type definitions by cluster analysis*. Western Journal of Applied Forestry 16(3), 101-105.

van Wagner C.E., 1968. *Fire Behaviour Mechanisms in a Red Pine Plantation: Field and Laboratory Evidence.* Canadian Department of Forestry. Dep Pub No. 1229.

van Wagner C.E.,1977. *Conditions for the start and spread of crown fire*. Canadian Journal of Forest Research 7, 23-34.

van Wagtendonk J.W., 1999. *Use of Thematic Mapper imagery to map fuel models*. In Proceedings of the 13th Conference on fire and forest meteorology. Lorne, Australia.

van Wagtendonk J.W., 2006. *Fire as a physical process*. Pp. 38-57 In: Sugihara, N. G., J. W. van Wagtendonk, J. Fites-Kaufman, K. E. Shaffer, and A. E. Thode (eds.). Fire in California's ecosystems. University of California Press, Berkeley. 578 p.

van Wagtendonk J.W., Root R.R., 2003. *The USE of multitemporal Landsat normalized difference vegetation index (NDVI) data for mapping fuels models in Yosemite National Park, USA.* International Journal of Remote Sensing 24, 1639–1651.

van Wilgan B.W., Le Maitre D.C., Kruger F.J., 1985. *Fire Modelling in South African Fynbos (Macchia) Vegetation and Predictions from Rothermel's Fire Model*. Journal of Applied Ecology 22, 207-216.

van Wilgan B.W., Le Maitre D.C., Kruger F.J., 1985. *Fire Modelling in South African Fynbos (Macchia) Vegetation and Predictions from Rothermel's Fire Model*. Journal of Applied Ecology 22, 207-216.

Vélez R., 1993*. High intensity forest fires in the Mediterranean Basin: Natural and socioeconomic causes.* Disaster Management 5, 16-20

Vélez R., 1997a. *Recent history of fires in Mediterranean area*. In: Balabanis P, Eftichidis G, Fantechi R (eds) Forest fire risk and management, Proceedings of the European School of Climatology and Natural Hazards course. European Commission, Brussels, pp. 15-26

Vélez R., 1997b. *Les feux de forêt en Espagne en 1997*. Forêt Méditerranéenne 18, 348

Verbyla D.L., 1995. *Satellite remote sensing of natural resources*. (Lewis Publishers, CRC Press: Boca Raton). 198 pp.

Viegas D.X., Palheiro P.M., Pita L.P., Ribeiro L.M., Cruz M.G., Olero A., Arrue B., Ramiro M.D., 2006. *Analysis of Fire Behaviour in Mediterranean Shrubs: the Gestosa fire Experiments (Portuga*l). In V International Conference on Forest Fire Research. D.X. Viegas (Ed.) 2006

Visual Learning Systems, 2002. LIDAR Analyst® 4.2 for ArcGIS® Reference Manual. Missoula, Mt, USA.

Walker D.A., Halfpenny J.C., Walker M.D., Wessman C.A., 1993. Long-term studies of snow-vegetation interactions. Bioscience. 43, 287-301.

Ward D., 2001. *Combustion chemistry and smoke. In Foreste fires: Behavior and ecological effects.* (Eds E.A. Johnson and K. Miyanishi) pp. 55-78 (Academic Press: San Diego, USA)

Waring R.H, Running, S.W., 1998. *Forest ecosystems : analysis at multiple scales*. San Diego Academic Press

Warren W.G., Olsen P.F., 1964. *A line intersect technique for assessing logging waste*. Forest Science 10:267-276.

Weise D.R., Regelbrugge J., 1997. *Recent Chaparral Fuel Modeling Effort*. Chaparral Fuel Modeling Workshop, Riverside, 1-12 March.

Werth L.F., McKinley R.A., Chine E.P., 1985. *The use of wildland fire fuel maps produced with NOAA AVHRR scanner data*. In Proceedings of the Pecora X symposium. pp. 326–331. (American Society for Photogrammetry and Remote Sensing: Falls Church, VA)

Whelan R.J., 1995. *The Ecology of Fire*. Cambridge University Press. 343 pp..

Whittaker R.H., 1967. *Gradient analysis of vegetation*. Biological Review 42, 207-264.

Whittaker R.H., 1975. *Communities and Ecosystems*. 2d ed. New York: Macmillan. 385 p.

Wikipedia, http://en.wikipedia.org/wiki/Object_Oriented_Image_Classification, last visited date October 06, 2005

Williams M., Rastetter E.B., 1999. *Vegetation characteristics and primary productivity along an arctic transect: implication for scaling up.* Journal of Ecology. 87, 885-898.

Wilson B.A., Ow C.F.Y., Heathcott M., Milne D., McCaffrey T.M., Ghitter G., Franklin S.E., 1994. *Landsat MSS classification of fire fuel types in Wood Buffalo National Park*. Global Ecology and Biogeography Letters 4, 33–39.

Wilson R.A., 1990. *Reexamination of Rothermel's fire spread equations in no-wind and no-slope conditions.* USDA For. Serv. Res. Pap. INT-434. 13 p.

Wright H.A., 1970. *A method to determine heat-caused mortality in bunchgrasses*. Ecology 51, 582–587.

Wright H.A., Bailey A.W., 1982. *Fire ecology: United States and southern Canada*. John Wiley and Sons, Inc. New York, 501 pp.

www.charlotte.utdallas.edu

www.fire.org

www.frcc.gov

www.fs.fed.us/land/wfas/fuels

Zhou X., Mahalingam S., Weise D., 2005a. *Modeling of Marginal Burning State of Fire Spread in Live Chaparral Shrub Fuel Bed.* Combustion and Flame 143, 183-198.

Zhou X., Weise D., Mahalingam S., 2005b. *Experimental Measurements and Numerical Modeling of Marginal Burning in Live Chaparral Fuel Beds*. Proceedings of the Combustion Insitute 30, 2287-2294.

Zwolinski M.J., 1990. *Fire effects on vegetation and succession*. In Effects of fire management of southwestern natural resources, Proceedings of the symposium, November 15-17, 1988, Tucson, Arizona, by J.S. Krammes, ed., United States Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.