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FUEL MODELS DEVELOPMENT TO SUPPORT SPATIALLY-EXPLICIT FOREST FIRE MODELLING IN EASTERN ITALIAN ALPS

Direttore della Scuola : Ch.mo Prof. Antonio Berti
Supervisore :Ch.mo Prof. Michele Scotton
Co-Supervisore: Ch.mo Prof. Tommaso Anfodillo

Dottorando : Rolando Rizzolo

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Summary

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Riassunto

Nelle Alpi gli incendi boschivi possono avere un impatto severo sulle foreste montane riducendo la loro capacità di protezione contro frane, valanghe e colate di fango e detriti (Moody and Martin 2001, Robichaud *et al.* 2007). A causa dei cambiamenti climatici, molti studi hanno evidenziato che l'impatto degli incendi boschivi in ambiente alpino sarà destinato ad aumentare nei prossimi anni (Elkin *et al*. 2013, Lorz *et al*. 2010, Wastl *et al*. 2012).

Un argomento chiave nella moderna gestione degli incendi boschivi è l'accurata mappatura dei combustibili forestali in modo da realizzare carte di rischio, piani antincendi boschivi ed interventi di riduzione del rischio incendi (Krasnow *et al.* 2009*)*. Esistono vari sistemi di classificazione dei combustibili forestali utilizzati dai vari enti che si occupano di incendi in USA, Europa, Canada e Australia. Molti di questi sistemi hanno le stesse categorie, componenti e variabili (Sandberg *et al.* 2001, Scott and Burgan 2005).

Un modello di combustibile è una descrizione generale delle proprietà dei combustibili forestali (es. carico, densità, contenuto calorico, ed umidità di estinzione) utilizzata nei software di predizione del comportamento del fuoco (es. FARSITE). I modelli di combustibile Standard sono stati sviluppati negli stati uniti da Anderson (1982) e più recentemente da Scott e Burgan (2005). I modelli di combustibile Standard che rispecchiano le caratteristiche della vegetazione locale possono essere utilizzati come input per la modellizzazione del fuoco, anche in combinazione con modelli di combustibile locali (Duguy *et al.* 2007, Arca *et al.* 2009, Jahdi *et al.* 2015). Ciononostante i modelli di combustibile sia Standard e sia locali sono stati raramente applicati nelle Alpi.

In questo studio abbiamo studiato la possibilità di definire dei modelli di combustibile locale per le Alpi Orientali Italiane, al fine di permettere un migliore l'utilizzo dei software di propagazione del fuoco.

La definizione dei modelli di combustibile locali è stata attraverso tre fasi di lavoro: Nella prima fase abbiamo studiato il regime degli incendi ed il comportamento del fuoco ed abbiamo testato l'ipotesi che la diminuzione dell'area bruciata sia in relazione con il miglioramento dell'efficienza del sistema antincendi boschivi che è avvenuto a partire dall'inizio del terzo millennio.. Nella seconda parte abbiamo misurato in bosco e analizzato le principali proprietà dei combustibili forestali. Nella terza parte abbiamo realizzato tre gruppi di modelli di combustibile utilizzando tre

diversi sistemi di classificazione (associazione alla tipologia forestale, classificazione Prometheus, classificazione per cluster). Quindi, utilizzando FARSITE (Finney 2004), abbiamo simulato dieci incendi avvenuti nella Regione del Veneto dal 2003 al 2013. Ogni incendio è stato simulato utilizzando sia i tre gruppi di modelli locali e sia i modelli Standard (Anderson 1982, Scott and Burgan 2005). Infine il gruppo di modelli con la migliore accuratezza nella simulazione dell'area bruciata è stato migliorato in modo da aumentare le sue capacità di simulare il reale comportamento del fuoco.

Nella Regione del Veneto c'è stata una diminuzione del numero di incendi per anno dal 1981 al 2004 ed una ancora più evidente diminuzione nell'area bruciata annuale. Sia in montagna che in pianura gli incendi sono generalmente di superficie e raramente superano i dieci ettari.

La distribuzione potenza assunta dalle aree bruciate sembra confermare il miglioramento dell'efficienza del sistema antincendio in quanto l'esponente della distribuzione è stato molto più alto nell'ultima decade rispetto alle due precedenti.

Nelle aree montane il carico di combustibili è in linea con quanto riportato in letteratura per tipologie forestali simili, mentre nei Colli Euganei è superiore al normale, probabilmente a causa di problemi fitosanitari che causano una elevata disponibilità di legno morto.

Abbiamo trovato differenze significative nel carico di combustibili fra le tipologie forestali (castagneti, orno ostrieti, impianti di conifera, cespuglieti), la differenza principale riguarda il carico di lettiera ($p<0{,}001$ in pianura, $p=0{,}0015$ in montagna). Sono state notate anche differenze significative fra i tipi di gestione forestale (ceduo, fustaia, abbandono), principalmente carico di cespugli ($p=0{,}0018$ in pianura) ed erbe ($p=0{,}0029$ in montagna).

La distribuzione dei carichi di combustibile distinti per classi diametriche non era mai normale ma sempre logaritmica o potenza, come normalmente riportato in letteratura.

I test dei modelli di combustibile hanno mostrato che i gruppi Prometheus e Cluster non hanno simulato accuratamente il comportamento del fuoco. I Modelli Standard (Anderson 1982, Scott and Burgan 2005) hanno funzionato generalmente bene, ed i modelli di combustibile per tipologia forestale hanno dato la migliore predizione dell'area bruciata, nonostante una frequente sottostima dell'altezza di fiamma e della velocità di avanzamento. Infine attraverso il processo di calibrazione abbiamo migliorato i modelli “Tipologia forestale” in modo da ottenere una migliore simulazione del comportamento del fuoco. Ottenendo così un nuovo gruppo di modelli Calibrati.

Per le future applicazione di simulazione del comportamento del fuoco suggeriamo di utilizzare i modelli di combustibile Calibrati

Abstract

Forest fires in the Alps can have severe impacts on mountain forests reducing their protection capacity against rock falls and avalanches and increasing flood runoff, mud and debris flows (Moody and Martin 2001, Robichaud *et al.* 2007). Due to climate change, several studies have shown that the impact of forest fires in the Alpine environment will increase in the coming decades (Elkin *et al*. 2013, Lorz *et al*. 2010, Wastl *et al*. 2012).

A key issue in modern forest fire management is the accurate mapping of forest fuels in order to determine spatial fire hazard, plan mitigation efforts, and active fire management (Krasnow *et al.* 2009*)*. Several surface fuel description systems are currently used by land management agencies in the USA, Europe, Canada and Australia, and most of these systems have the same categories, components and description variables (Sandberg *et al.* 2001, Scott and Burgan 2005).

A generalized description of fuels based upon average fuel properties is called a “fuel model”. A fuel model is a set of fuelbed inputs (e.g. load, bulk density, fuel particle size, heat content and moisture of extinction) used by a specific software for predicting the fire behaviour (e.g. FARSITE). Standard fuel models were developed in the USA by Anderson (1982) and more recently by Scott and Burgan (2005). Standard fuel models that fit the main local vegetation characteristics can be used as input for fire spread modelling and in combination with custom fuel models when available (Duguy *et al.* 2007, Arca *et al.* 2009, Jahdi *et al.* 2015). However, the Standard or custom fuel models have seldom been applied in the Alps.

In this study we tested the possibility of defining some custom fuel models for the Eastern Italian Alps, which might allow a more reliable fire behaviour prediction when fire simulator systems are used.

The custom fuel models definition was done by means of three steps: In the first step we studied local fire regime and fire behaviour and we tested the hypothesis that the decrease in burned area is related to an improvement in fire-fighting efficiency since the beginning of the 3rd millennium. In the second step fuel properties were measured in the field and analyzed. In the third step we made three fuel model sets based on three different approaches (Forest type association, Prometheus classification, Cluster classification). Then, using FARSITE (Finney 2004), we simulated ten fires that occurred in the Veneto Region from 2003 to 2013. Every fire was simulated using the three

custom model sets and the Standard fuel models (Anderson 1982, Scott and Burgan 2005). Lastly, the fuel model set having the higher accuracy was adjusted in order to improve its performance in simulating real fire behaviour.

In the Veneto Region, there was a decreasing number of fires per year from 1981 to 2004 and a much more evident decrease in the annual burned area. Fires in both mountain areas and the lowlands usually behave as surface fires and the burned area is seldom larger than ten hectares.

We tested the hypothesis that the decrease in burned area is related to an improvement in fire-fighting efficiency since the beginning of the 3^{rd} millennium. The power-law distribution of burned areas seems to confirm that suppression efficiency has been improved because the exponent of the power-law distribution was much higher in the last decade than in the previous two.

In mountain areas fuel load paralleled what is reported in the literature for similar forests, but in the lowlands fuel load appeared much higher, probably because those forests are affected by phytosanitary problems that cause a higher amount of deadwood.

We found significant differences in fuel load among vegetation types (chestnut, hop hornbeam forests, conifer plantations and shrubland), The most significant difference was litter load ($p<0.001$ in the lowlands; $p=0.0015$ in mountain areas). Significant differences were also found between forest managements (coppiced, high forest, unmanaged). Mainly shrubs load ($p<0.0018$ in the lowlands) and herbs ($p=0.0029$ in mountain areas).

The fuel distribution in size classes was never normal but, as commonly reported in the literature, it followed a logarithmic or a power-law trend.

The tests on fire behaviour fuel models showed that Prometheus and Cluster fuel model sets led to inaccurate fire behaviour predictions. Standard fuel models (Anderson 1982, Scott and Burgan 2005) generally performed well and Forest type fuel models were the best in predicting fire behaviour, despite a frequent underestimation of flame height and rate of spread. By using a calibration process, we modified the Forest type fuel models and improved the performance in FARSITE. The resulting Calibrated fuel models could be suggested for further fire behaviour applications in the Eastern Italian Alps.

General Introduction

Fire regime in the Southern slope of the Alps differs from those of the Mediterranean area and in the North US or Australia: the main fire season occurs in winter, fires are mainly orographic driven and very often human-ignited.

The high population density, the slopes instability and the tourism-based economy would require a prompt and efficient fire suppression. However, the unpredictable fire distribution among years and the relatively low burned area compared to the Southern Regions of the country (Corpo Forestale 2016), leads that the forest fire danger is often underestimated and less studied than in others countries, as Spain, France, Greece and Portugal.

In recent years, Several studies showed that the risk of forest fires in the Alps will increase in coming decades because of the impact of climate change, the number of weather extremes with longer dry periods, high temperatures and generally less precipitation (Elkin *et al*. 2013, Lorz *et al*. 2010, Wastl *et al*. 2012). Moreover, Conedera *et al*. (1996), Conedera and Tinner (2000) and Goldammer and Bruce (2004) pointed out that forest fires should not only be associated with an increase in drought periods but also with the human influence on forest structure and fuel availability.

Fire occurrence is determined by different anthropic and environmental factors. Several studies reported that the variability in the burned areas was mainly related to weather/climatic factors, while fire ignition was driven by human activity and lightning (Flannigan and Harrington 1988, Viegas and Viegas 1994, Flannigan and Wotton 2001, Pausas 2004). For example, in the Eastern Italian Alps with a population of about 3M people and a surface of 3.4M ha (ISTAT 2001), 98% of fires are human-ignited and very often forest fires spread in wild-urban interfaces.

In the Alps, similarly to other areas, fire control policies have been strengthened during the second half of the 20th century thus leading to a general decrease in the burned area (Conedera et al. 2004, Zumbrunnen *et al.* 2011).

A key challenge in modern wildfire mitigation /suppression is the accurate mapping of forest fuels for determining spatial fire hazard, for planning mitigation efforts, and for managing actively the fires (Krasnow e*t al.* 2009). It is pivotal, therefore, to implement accurate surveys on the amount of plant fuels, and their susceptibility to burning. Indeed the most advanced countries in the management of forest fires (such as Canada, USA, Australia) have already mapped the distribution and amount of forest fuels in the most susceptible areas.

Several surface fuel description systems are currently in use by land management agencies in the Unites States, Europe, Canada and Australia, and most of these systems have the same categories, components and description variables (Sandberg *et al.* 2001, Scott and Burgan 2005). The main distinction between the existing fuel description systems is more in the approach used to create them rather than their accuracy, application and implementation in fire management (Keane 2013). The most common description system is the indirect one in which vegetation cover maps are used to create “crosswalks” to fuel characteristics (Keane *et al.* 2002, Stratton 2006). This method is problematic because fuels are not always correlated well with vegetation type and the fine-scale variability of fuels within each polygon of similar vegetation is not accurately reflected (Krasnow *et al.* 2009).

In general a forest fuel can be defined as a dead and live biomass available for fire ignition and combustion (Albini 1976). Due to peculiar properties related to tree species, fine structure, size and chemical composition fuel particles widely change within a forest and among forest types. Therefore there is a need in simplifying the wide fuel variability because software implemented for modelling fire behaviour, fire danger or smock emissions require a finite number of type of particles to which assign a specific combustion property (Keane 2013).

Indeed, in most of the fire behavior prediction systems developed for wildfire managers, the fuel data inputs are fire fuel “models” (i.e. aggregate of certain types of fuels), which are characterized by fuel components binned by particle diameter size (Anderson 1982, Scott and Burgan 2005). Properties of fuel components can be defined by different variables, such as heat content, mineral content and density, but the most important variable s is fuel loading i.e. the biomass per unit of area (e.g. Mg ha^{-1})(Pyne *et al.* 1996).

Commonly used fire behavior fuel models were initially developed for use in the United States by Anderson (1982) and more recently by Scott and Burgan (2005). The use of these fuel models outside their original area requires local validation to ensure they are representative of local fuel conditions. If not then the derivation of custom fuel models may be required.

Despite their importance, unfortunately, information about forest fuels in the Alps are relatively rare. Only few local studies are available (Camia 1994, Marchetti and Lozupone 1995, Veneto 1999, Ascoli et al. 2007, Arpaci *et al.* 2011, Ascoli *et al.* 2015), and large scale studies with systematic data collection are still missing.

Effects of fuel on fire behaviour are typically estimated using physical or empirical propagation models (McArthur 1967, Rothermel 1972). Such models are used for risk assessment and real-time fire simulation, and are therefore vital for planning fire suppression and fuel management *(Keane et al.* 2002). Several surface spread models have been developed under many conditions in different areas around the world, particularly where wildfires are threatening forests, valued resources and human lives (Pastor *et al.* 2003, Perry 1998, Sullivan 2009).

FARSITE is a spatial and temporally explicit fire simulation system developed at Missoula Fire Sciences Laboratory of the USDA Forest Service and is still currently one of the most used and user friendly simulators. The simulator, which is a semi-empirical model based on Rothermel's (1972) surface fire spread model, simulates fire growth using Huygens's principle wave propagation and fire intensity using Byram (Byram 1959) equation. FARSITE has been widely calibrated in the US (Finney and Ryan 1995, Finney 1998).

The ultimate goal of this work is to test the possibility of defining some custom fuel models in Eastern Italians Alps which might allow a more reliable fire behavior prediction when fire simulator system are used.

Defining the properties of a fuel model (i.e. fuel load, partitioning of particles size etc) is a complex and time-consuming activity and requiring distinct steps. The First step is to have a good knowledge of local fire regime and common fire behaviour in the study area. It is needed for selecting the study areas, the forest types to study and, at the end of the process, the fires where to test fuel models. The second step is related to the measurements of fuel properties in the field (e.g. measuring fuel load size od fuel particles etc). The third step deals with the choice of the most suitable and reliable approach for defining a given fuel model. The last step deals with testing the capacity of the defined fuel model, once used within a fire simulator system to allow a precise prediction of fire behavior.

In this thesis, we have separated these logical steps in three chapters:

In the first chapter, we used fires data from the last 30 years for making all the statistics needed to underhigh forest the actual fire regime and possible changes through time. Since local fire regime is strongly influenced by suppression activities, we gave particularly attention to the connections between burned areas size and suppression efficiency. Then we proposed a new method to estimate fire suppression efficiency.

In the second chapter, all the fuels field data collected during two years were reported and analyzed. We studied fuel distribution and fuel load correlation whit environmental factors, then we used three of the classification methods described by Keane (Keane 2013) in order to build three different custom fuel models sets.

In the chapter three, we tested the three custom fuel models sets by simulating ten real fires using FARSITE (Finney 2004). In addition, in the same fires, we tested also the Standard fire fuel models (Anderson 1982, Scott and Burgan 2005). Then we evaluated which among the four fuel series had the best accuracy in case study simulations. At the end, we calibrated the fuel models set having the highest accuracy in order to improve its performance in simulating real fire behaviours.

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Chapter I

Forest fires in the Eastern Italian Alps

Introduction

Wildland fires in the Alps can have severe impacts on mountain forests affecting their protection capacity again strock falls and avalanches and increasing flood runoff, mud and debris flows (Moody and Martin 2001, Robichaud et al. 2007).

The Southern part of the Alps has a complex fire regime that differs from what is usually found in the Mediterranean area and in North America or Australia: the main fire season is winter, fires are usually human ignited and orography-driven.

The relatively high population density, geological fragility and tourism-based economy require prompt and efficient fire suppression. However, the uneven fire distribution between years and the relatively small area burned compared with the Mediterranean part of Italy (Corpo Forestale 2016), mean that forest fire danger is often underestimated and less studied than in Mediterranean regions and other Mediterranean countries like Spain, France, Greece and Portugal.

The Alpine environment is highly diverse in terms of climate, geology and topography, which lead to different levels of susceptibility to fires (Arpaci *et al.* 2014). Several studies showed that the risk of forest fires in the Alps will increase in coming decades because of the impact of climate change, the number of weather extremes with longer dry periods, high temperatures and generally less precipitation (Elkin *et al*. 2013, Lorz *et al*. 2010, Wastl *et al*. 2012). Moreover, Conedera *et al*. (1996), Conedera and Tinner (2000) and Goldammer and Bruce (2004) pointed out that forest fires should not only be associated with an increase in drought periods but also with the human influence on forest structure and fuel availability.

Fire management aims to reduce the impact of forest fires on the Alpine environment through prevention and mitigation measures. In this context, knowledge about fire behaviour and fire intensity of the main fire prone vegetation types is a prerequisite for the planning of operational procedures (Arpaci *et al.* 2011).

Fire occurrence is determined by different human and environmental factors. Several studies reported that most of the variability in the areas burned is related to weather/climatic factors, while fire ignition is related to human factors and lightning (Flannigan and Harrington 1988, Flannigan and Wotton 2001, Pausas 2004, Viegas and Viegas 1994). Changes in spatial and temporal fire behaviour occur in relation to changes in environmental conditions, and weather is the most rapidly variable component in both space and time (Pyne *et al*. 1996).

Similarly to other geographical areas, fire control policies in the Alps have been strengthened during the second half of the 20th century, determining an overall decrease in the area burned in the Alpine region (Conedera *et al*. 2004, Zumbrunnen *et al*. 2011). Autumn-winter and early-spring anthropogenic slope-driven surface fires mainly characterize the current fire regime (Pezzatti *et al*. 2009), with a minor but increasing percentage of summer ignitions due to lightning (Conedera *et al*. 2006, Müller *et al*. 2013, Reineking *et al*. 2010). The resulting small average fire size of 9ha (Valese *et al*. 2011) is due to a combination of favourable factors such as the relatively mild weather conditions compared to other regions (Brang *et al*. 2006), the small-scale variability in plant species composition and flammability (Pezzatti *et al*. 2009), and effectiveness of fire suppression (Conedera *et al*. 2004).

The Eastern Italian Alps have a population of about 3M people and a surface of 3.4M ha (ISTAT 2001), so population is a key factor for determined fire regime. 98% of fires are human ignited and forest fires very often spread in the wild-urban interface.

The studies on fire characterisation in the Alps have increased in recent years (Pezzatti *et al*. 2009, Vacik *et al*. 2011, Arpaci *et al*. 2011, Wastl *et al*. 2012, Valese *et al*. 2014). However, the possibility of extensive study in the Alps is limited by political fragmentation of the area between eight countries. A recent common effort to characterize forest fires in the Alps has been the Alp FFirs European project (Valese *et al*. 2010).

The goals of this study are to characterize the actual fire regime in the Eastern Italian Alps and to evaluate the suppression efficiency influence on fire regime.

Materials and methods

Study area

The study area is the Veneto Region; it is located in Northeast Italy, between 46.68° and 44.79° latitude and between 10.63° and 13.09° longitude (Figure 1.1). The region is about 18,264 km^2 and has a high diversity in climate, geology and topography, which leads to different levels of susceptibility to fire. The forest area is about 414,893 ha and is mainly concentrated in the mountains (Del Favero 2006) (Figure 1.4). The region is divided in three very different environmental zones: The Alpine part in the north, with high mountains (15% of the region); a low mountains and hills area called Prealpi, in the centre of the region (30% of the region); a large lowland area including two ranges of hills, the Venice lagoon and 150 km of beaches in the south (55% of the region) (Figure 1.2).

The Alpine area is characterised by steep and tall mountains that reach between 2000 and 3600 m. The climate is continental with cold winters and high temperature excursions. Precipitations are about 1000 mm/year. The area is mainly covered by forests, apart from in the cultivated valley bottoms and at high elevations where there are mainly alpine tundra and rocky walls. In this part of the region, forests are formed mainly by softwood species (*Abies alba* Mill., *Picea abies* Kars., *Larix decidua* Mill., *Pinus silvestris* L., *Pinus cembra* L. and *Pinus mugo* Turra*)* apart from at low elevation where *Fagus sylvatica* L. is the main species. Forests are mainly managed for timber production where it is cost effective.

The Prealpi area has peaks between 1000 and 2000 m a.s.l. and a semi-continental climate with higher temperature than the mountain area and higher precipitation (1300 mm/year). It is covered mainly by hardwood forests: *Castanea sativa*, *Ostrya carpinifolia* Scop., *Quercus spp.*, *Robinia pseudoacacia* L. at low elevations and *Fagus sylvatica* at high elevation. Softwoods are spontaneous only at higher elevations. Softwood plantations are quite common out of their spontaneous distribution area. They are composed mainly of *Picea abies*, *Pinus nigra* Arnold and *Pinus silvestris*. Coppicing is the most common management method in hardwood forests (Salmaso *et al.* 2010)

Figure 1.1- Veneto Region location

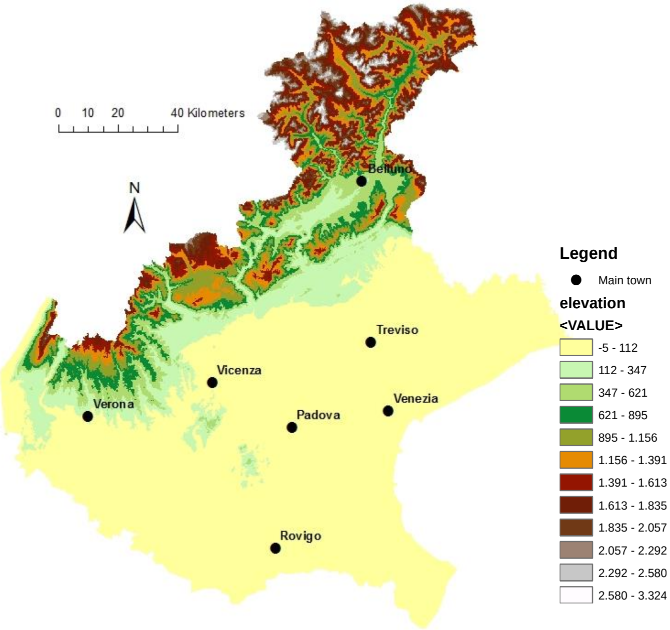


Figure 1.2 - Orography

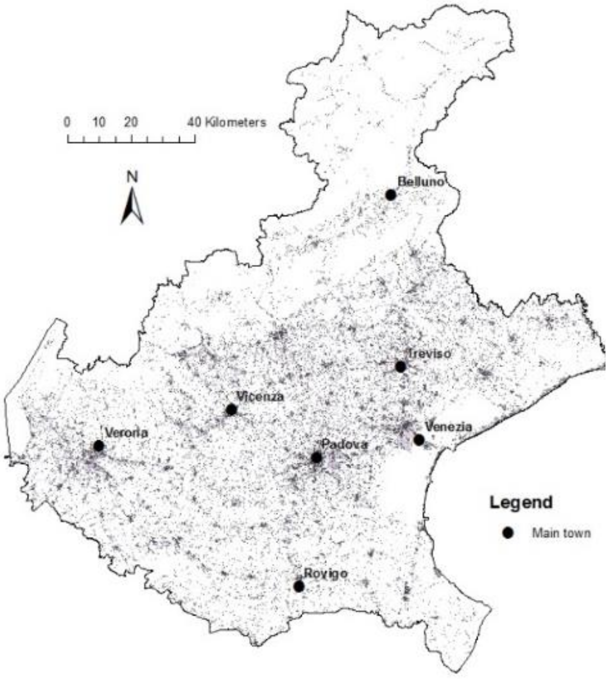


Figure 1.3- Urban areas

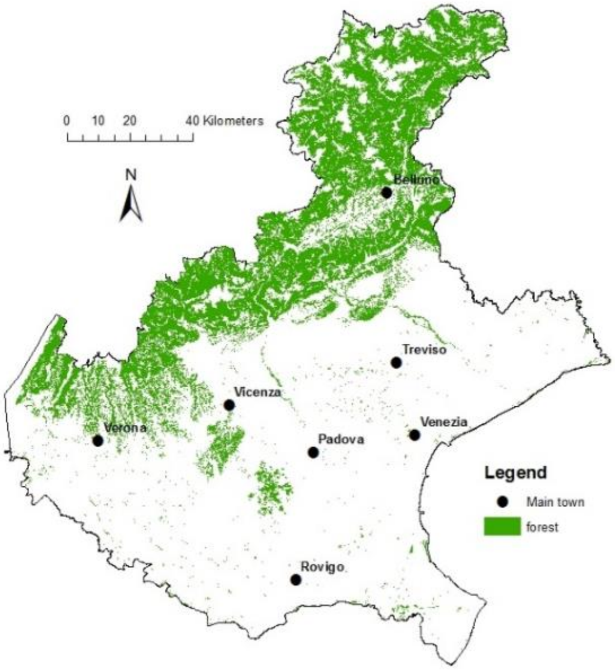


Figure 1.4 - Forest cover

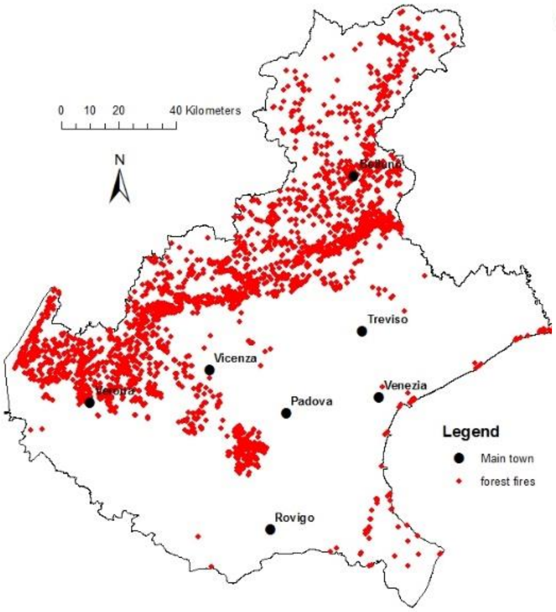


Figure 1.5 - Forest fires

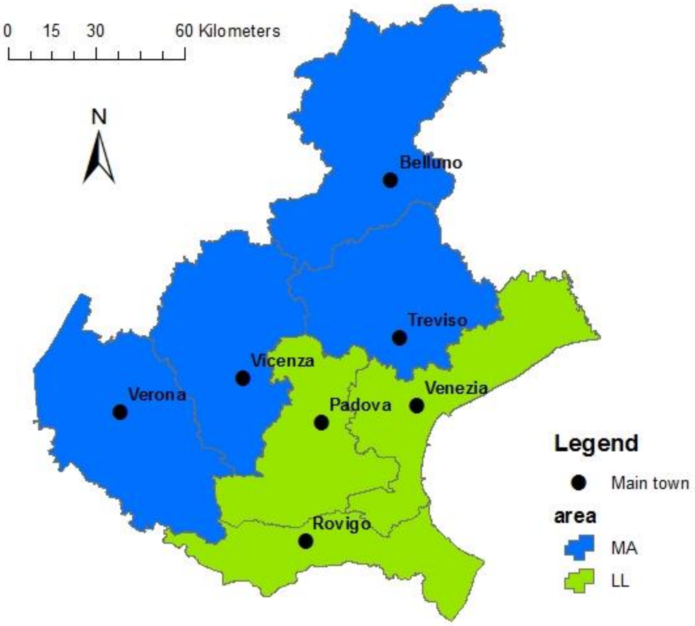


Figure 1.6–Study areas

The lowland is mainly urban and agricultural land. There are very few forests, they are concentrated on the isolated hills (Colli Berici, Colli Euganei), along the main rivers and coast (pine plantations). The climate is continental with very warm summers and high humidity. Precipitation is usually less than 1,000 mm/year. The hills are mainly covered by *Castanea sativa*, *Ostrya carpinifolia*, *Quercus pubescens* Will. and *Robinia pseudoacacia*, with some Mediterranean species like *Quercus ilex* L. and *Arbutus unedo* L.(Salmaso *et al.* 2010). Along the coast the natural vegetation is *Quercus ilex* forest but in most cases it has been replaced by pine afforestation (*Pinus pinea* L., *Pinus pinaster* Aiton). Re-naturalisation efforts are under way in some plantations (Salmaso *et al.* 2010).

Veneto is a very populated region (Figure 1.3). Most of the population live in the lowlands, but the mountain area is also densely populated compared with other mountain areas in the world (110 habitants per km^2; ISTAT 2011). The mountains had about 1M tourists in 2014 (Coronella *et al*. 2014). Considering local population and tourists, human pressure on the natural environment is very high, and can increase both the fire risk and the fire exposure.

The fire regime is very different between the mountain part of the region (Dolomiti, Prealpi) and the lowlands (coast and hills). The mountain area of the region has a typical alpine fire regime where the main fire season is in winter and the fires are slope-driven, while the lowlands have a typical Mediterranean fire regime where the main fire season is in summer. For this reason, we chose two separate study areas for the two parts of the region. We included the fires occurring in the provinces of Verona, Vicenza, Belluno and Treviso in the mountains statistical area (MA in the text) and the fires in the provinces of Padova, Venezia and Rovigo in the lowlands statistical area (LL in the text).

Forest fire and geographic data

Data on forest fires in Veneto are recorded by Veneto Region. The regional database contains information about fires from 1989 onwards. The information is the same as that recorded in the national forest statistical database managed by National Forest Corps (Corpo Forestale dello Stato). Since 2002, all fires bigger than 100 m^2 have been recorded, while in the past small fires were often not reported, so an underestimation in fire number and burned area is possible for the earlier years. To limit the error in number of small fires, we considered only the fires bigger than 999 m^2 in the statistics.

Information about the regional firefighting organisation and its evolution over the last 30 years has been provided by regional civil protection and regional forest services.

In 2007 the Veneto Regional Administration compiled a land use map covering the whole region. The map is based on photogrammetry and has a nominal scale of 1:10,000 (Veneto 2016). On the map, forests are classified according to very detailed local forest types (Del Favero *et al*. 2004, Del Favero 2006) based on the main forest species. We used the regional land use map to measure forest type surface areas.

Fire risk meteorological index

We obtained the Fire Weather Index (FWI) of the days when the main fires happened (Van Wagner and Forest 1987) from the Regional Agency for Environment Protection (ARPAV). The index is calculated every day at 13:00, using the data of 41 weather stations distributed in the whole

Veneto region (Valese 2008, Tardelli *et al*. 2012). We reported the FWI value of the weather stations closer to the fires.

Data analysis

In the analysis of fire regime we considered the trend in number of fires and extent of burned area, the season of occurrence, the fire types and the ignition causes. Then we analyzed the vegetation found in burned areas and if it had some trends. Analysis were separated between LL and MA study areas. Then we analyzed in detail the main fire drivers in the largest fires occurred in the last ten years. We selected only the last ten years because we were interesting in focus on actual fire regime and because of the difficult in finding accurate information on previous fires.

We used the cumulative distribution function (CDF) for analysed fuel distribution (Zwillinger and Kokoska 1999). In probability theory and statistics, the CDF, or just distribution function, describes the probability that a real-valued random variable X with a given probability distribution will be found to have a value less than or equal to x. In the case of a continuous distribution, it gives the area under the probability density function from minus infinity to x. Cumulative distribution functions are also used to specify the distribution of multivariate random variables. The cumulative distribution function of a real-valued random variable X is the function given by:

$$F_x(x) = P(X \leq x) \qquad (12)$$

Where the right-hand side represents the probability that the random variable X takes on a value less than or equal to x. The probability that X lies in the semi-closed interval (a, b), where a < b, is therefore:

$$P(a < X \leq b) = F_x(b) - F_x(a) \qquad (13)$$

Results

In Veneto Region, from 1981 to 2014, there were 3,231 fires and a total burned area of 25,848.5 ha (Attachment A, Figure 1.7). The average fire size is 8.0 ha. The number of fires is unevenly distributed between years, the average number per year is 95 and the average burned area per year is 760.3 ha. From 1981 to 2004, the number of fires decreased but not very strongly. The decrease in burned area is much more evident (Figure 1.7). From 2004 to 2014, there is a stability in burned area, apart from the exceptions in 2011 and 2012.

In LL, the number of fires and the burned area are a small part of the regional total (Figure 1.8). From 1981 to 2014, 381 fires were recorded for a total burned area of 1,174.3 ha. Number of fires and burned area are quite constant apart from a few peaks corresponding to years with a very dry summer (1990-1993, 2003, 2012). The average burned area is 3.1 ha (Attachment A). There is no clear trend by the years.

In MA, 2,850 fires were recorded from 1981 to 2014, for a total burned area of 24,674.2 ha (88% of total regional fires). Figure 1.9 shows a slight decrease in number of fires overtime and a more evident decrease in burned area. In particular, from 2004, the burned area stabilized at a very low level, apart from in 2011 and 2012 when winters were very dry (ARPAV 2016). The average burned area is 8.7 ha. Figure 11 shows how the average burned area strongly decreased after 2003, with the only exception being 2012. The average burned area from 1981 to 2003 is 9.2 ha, from 2004 to 2014 it is 2.0 ha (Attachment A).

The two study areas have a very different seasonal fire distribution. In LL fires are mainly in spring and in summer (Figure 1.11). The main peak is in July and August (42% of fires; 50% of burned area). In MA fires occur mainly in late winter (Figure 1.11), from January to April (77% of fires; 79% of burned area).

In LL, fire distribution by size (Figure 1.12) shows that the most fires are very small (<1 ha; 48%) or small (1<x<10 ha; 45%). Just 7% of fires are bigger than 10ha but they burned 55% of the burned area. None is bigger than 100 ha. The largest burned area recorded is 80 ha. In MA, the distribution in size classes (Figure 1.13) shows a similar trend to the lowlands but with a stronger influence of the big fires. Fires bigger than 100 ha are 2% of the total and they burned 55% of the total burned area. The biggest fire recorded is 773 ha.

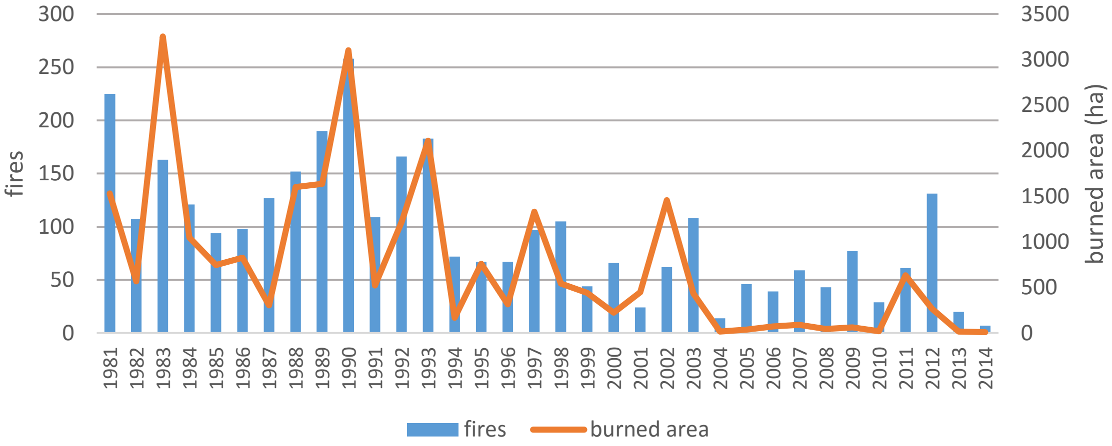


Figure 1.7– Whole region - Forest fires and burned area (1981-2014)

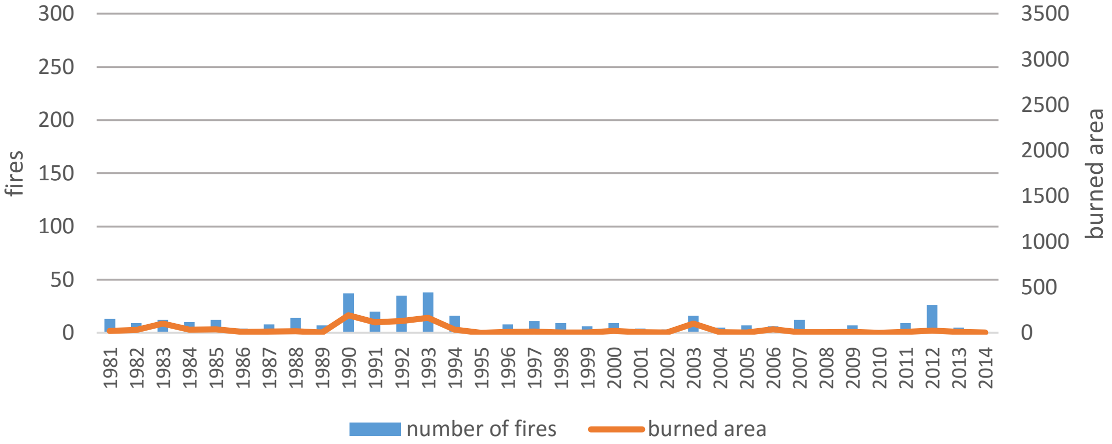


Figure 1.8–LL - Forest fires and burned area (1981-2014)

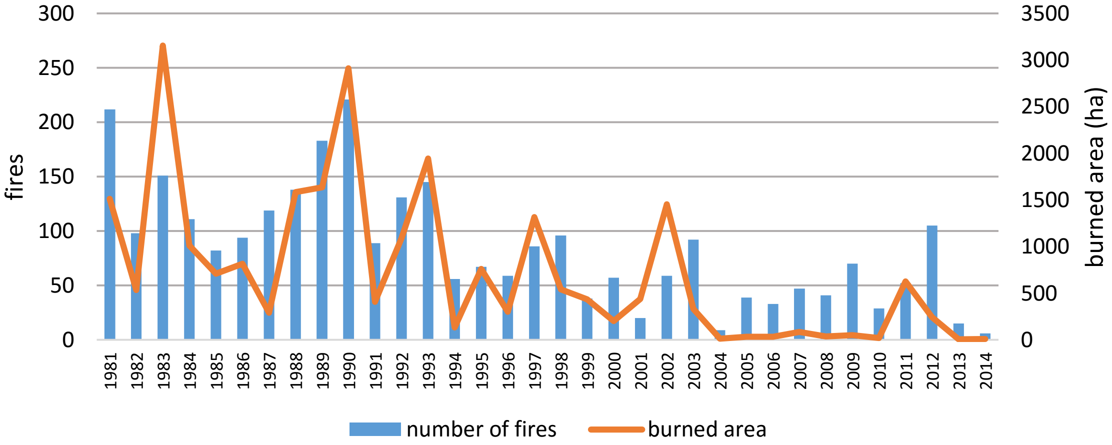


Figure 1.9–MA - Forest fires and burned area (1981-2014)

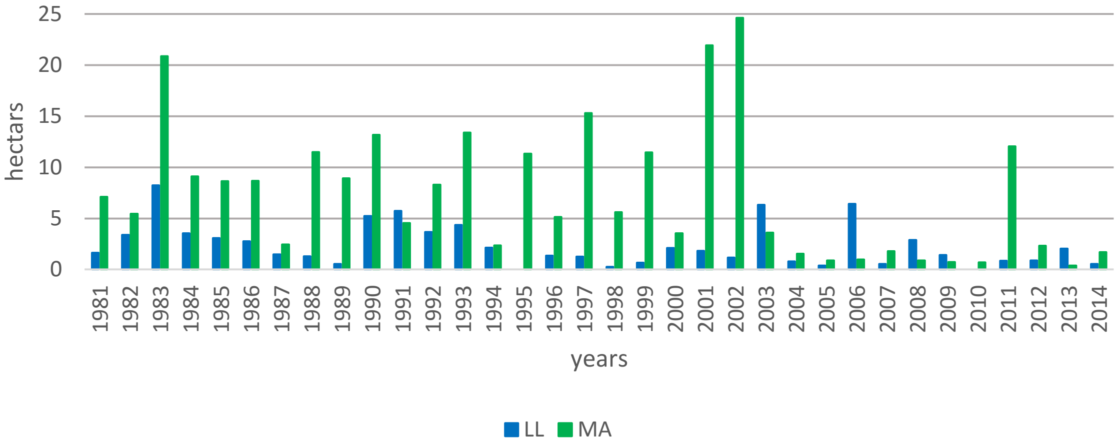


Figure 1.10- LL and MA – Average burned area

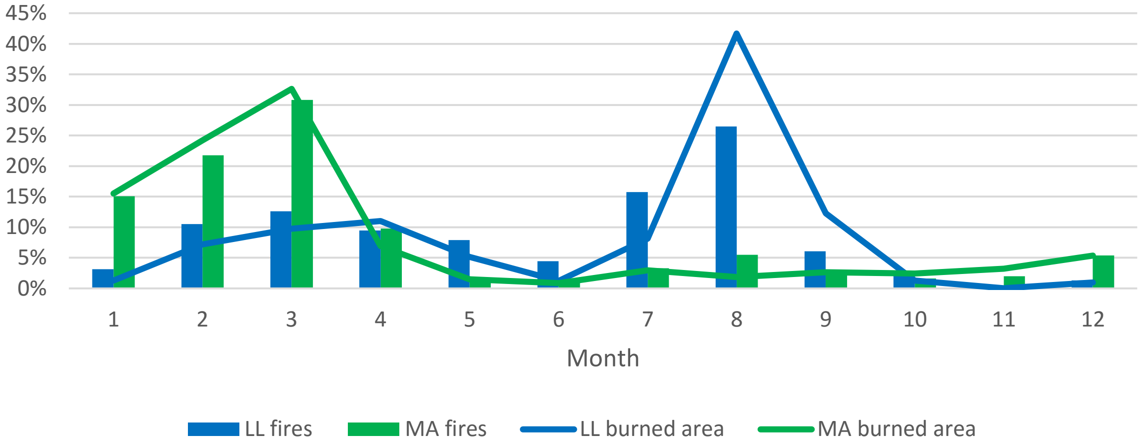
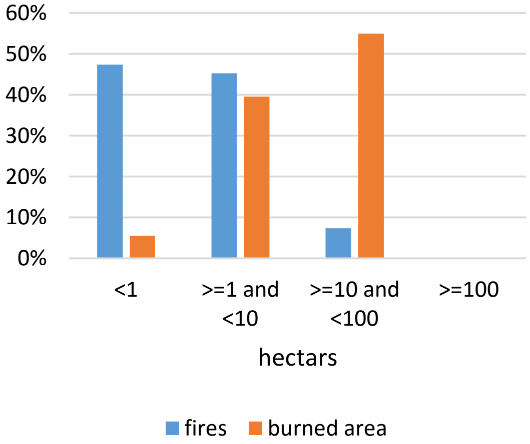


Figure 1.11- LL and MA **-** Seasonal distribution



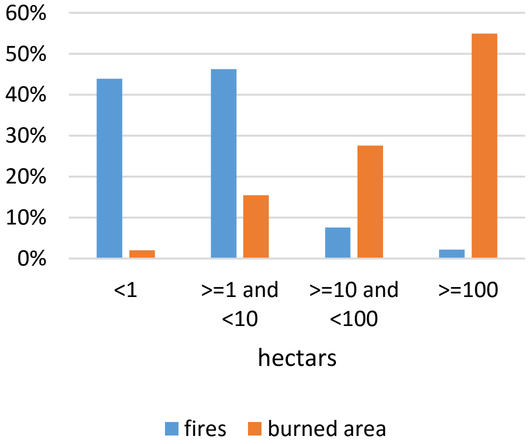


Figure 1.12–LL - Fire size distribution

Figure 1.13– MA - fire size distribution

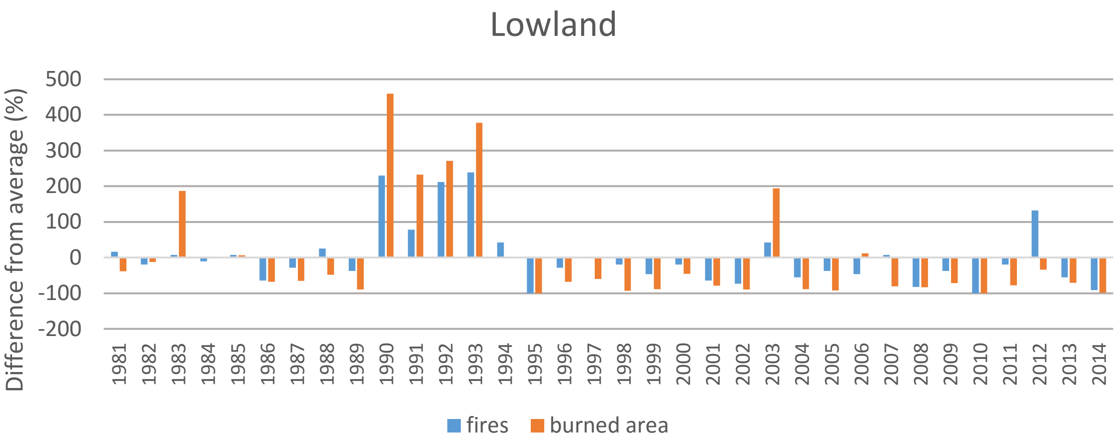


Figure 1.14– LL - Difference from average in number of fire and burned area

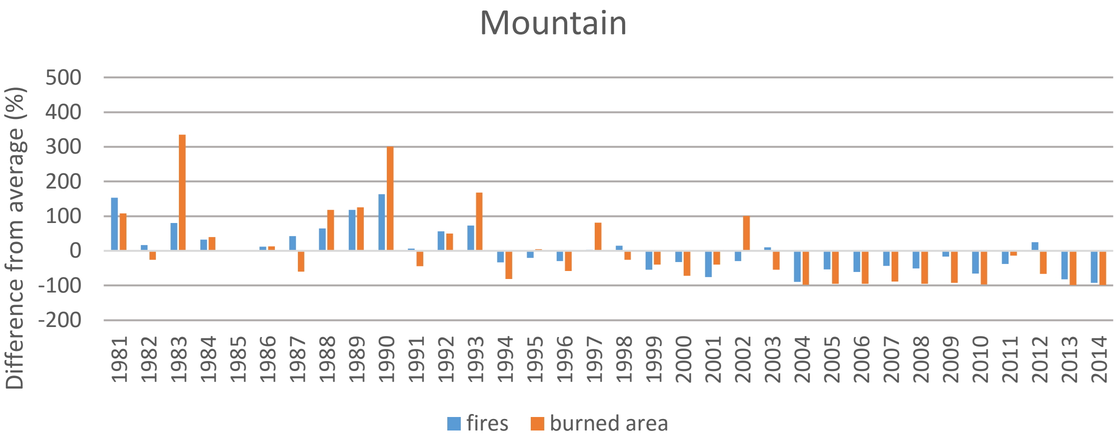


Figure 1.15– MA - Difference from average in number of fire and burned area

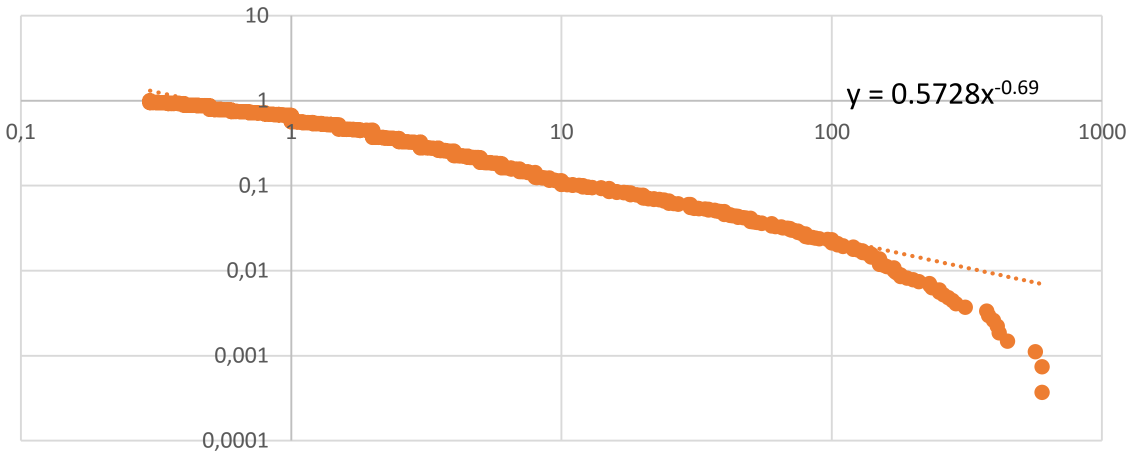


Figure 1.16– Whole region (1981-2014) - Log10 (Burned area CDF). $R^2 = 0.97$

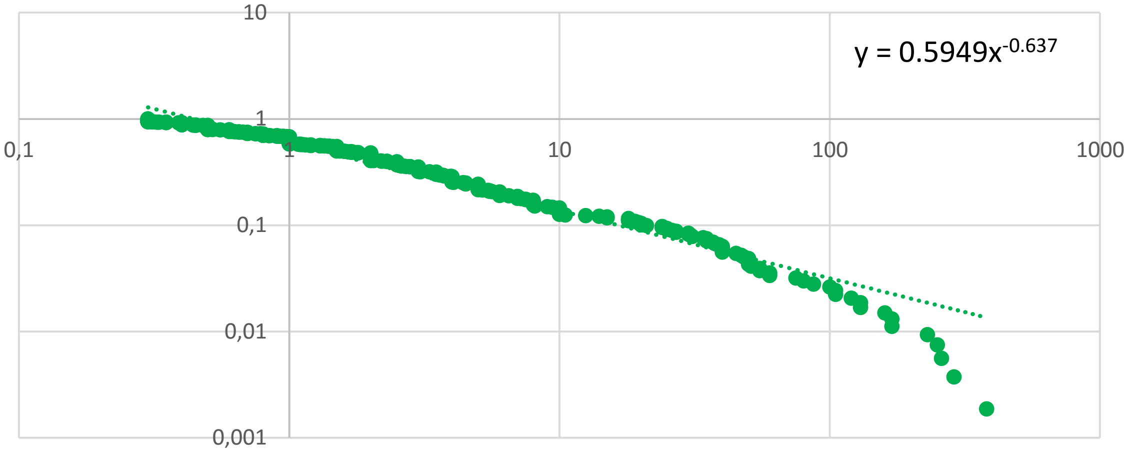


Figure 1.17– Whole Region (1995-2004) - Log10 (Burned area CDF). R^2 = 0.96

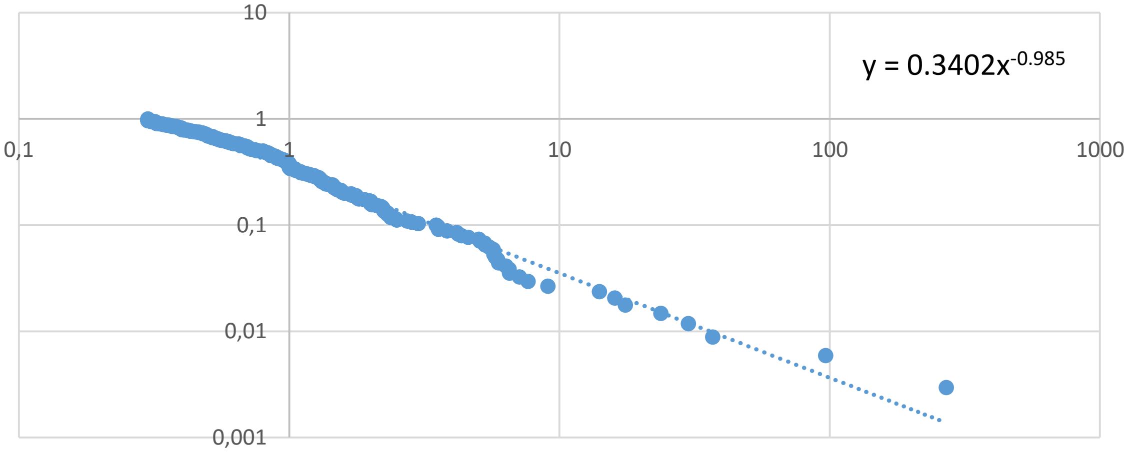


Figure 1.18– Whole Region (2005-2014) - Log10 (Burned area CDF). R^2=0.98

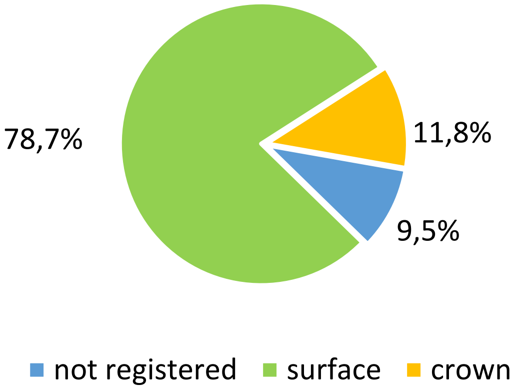


Figure 1.19 – LL - Type of fire

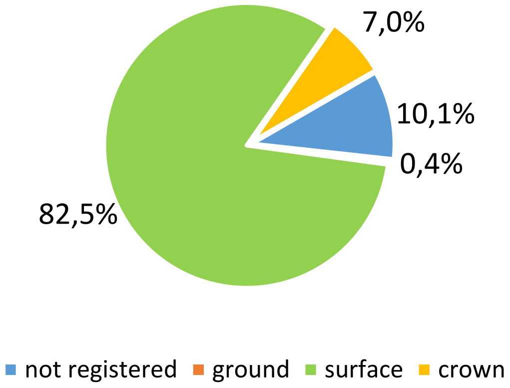


Figure 1.20 – MA - Type of fire

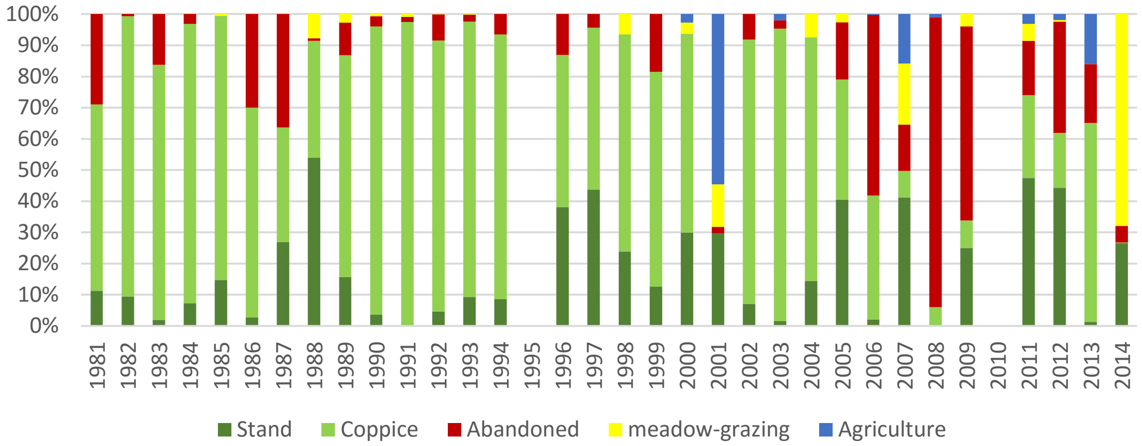


Figure 1.21– LL - Burned area and land use

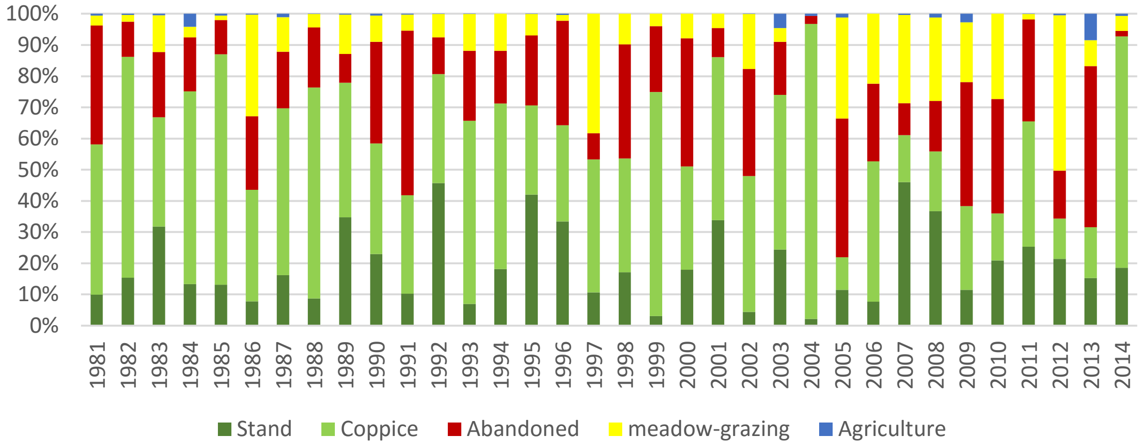


Figure 1.22– MA - Burned area and land use

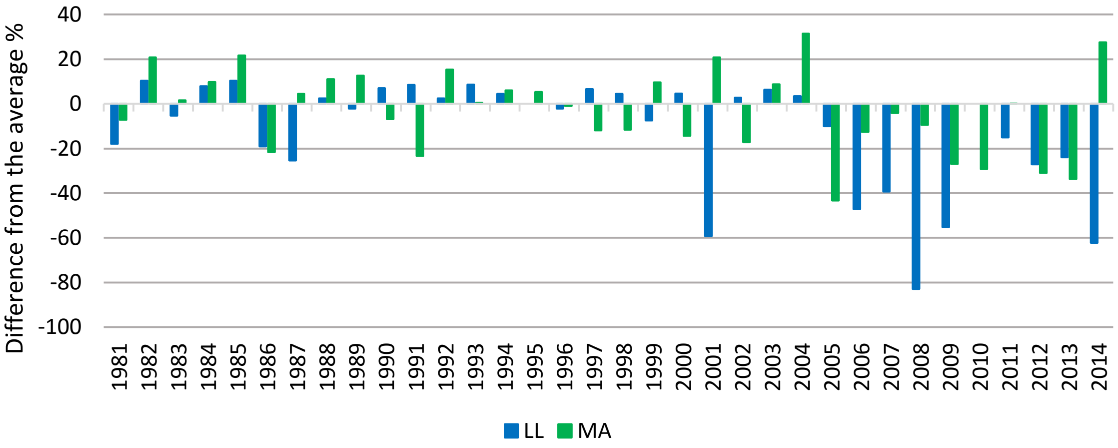


Figure 1.23– LL and MA–difference from the average in wooded area burned

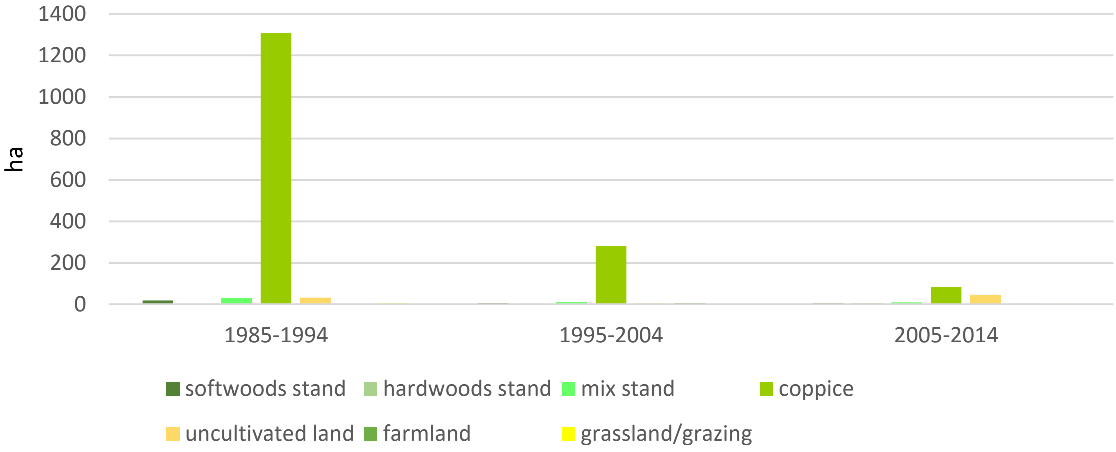


Figure 1.24– LL– burned area and land use separated in ten-year periods

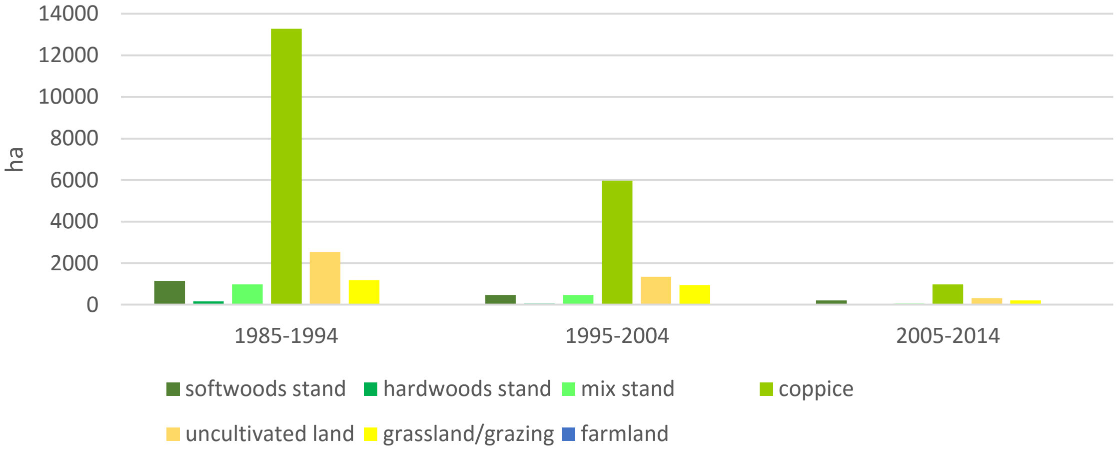


Figure 1.25– MM– burned area and land use separated in ten-year periods

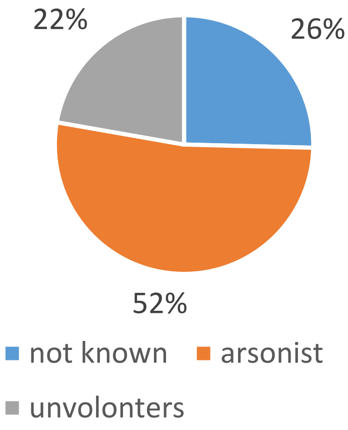


Figure 1.26–LL – Fire ignition causes

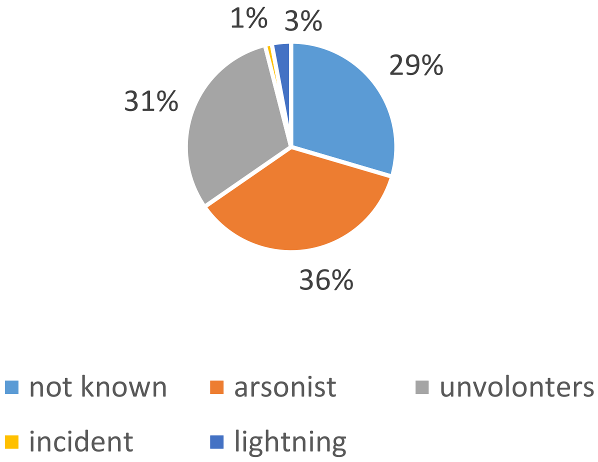


Figure 1.27 – MM – Fire ignition causes

Figures 1.14 and 1.15 Shows how in both the study areas, from 1995 to 2014 the number of fires and the burned area are usually below the average of the full period. There are just few exceptions in 1997, 1998, 2002, 2003 and 2012.

Considering the regional level, the Cumulative Distribution Function follows a power-law distribution (Figure 16). In Figures 1.17 and 1.18 we separated the last 10 years from the previous 20 years. The CDF slopes appeared markedly different with a steeper slope (-1.985) in the most recent years compared to previously (slope -1.637).

As far as fire behavior is concerned, surface fires are prevalent the region (78.7% in LL, 82.5% in MA), while crown fires are relatively uncommon (11.8% in LL, 7% in MA). Ground fires are very rare but possible, 0.4 % in MA (Figures 1.19, 1.20).

In LL, coppice forests are by far the most common burned area (57% of total) (Figure 21). In the period 1981-2014 coppices burned area decreased more than the burned area in the other formations (Figure 21, 24). In the last decade (2005-2014) there is an increase in percentage of non-forest burned area, due to the strong decrease in forest burned area and also to a slight increase in abandoned lands burned area (Figure 1.23, 1.25).

In MA the most common burned land use is coppiced forests (66% of total) but there is a higher percentage of non-forest area burned compared with the lowlands (34%). Also in this area the percentage of forest burned area decreased after 2004. The only exception is 2014 when the total burned area was anyway very low (Figure 1.23).

The regional forest map (Del Favero 2006) reported a forested area of 7059 ha in LL and 402,613 ha in MA. 53% of forests managed as coppice and 43% managed as high forest.

The percentage of forested burned area per year is about 0.46% in LL and 0.12% in MA. The larger percentage in LL is due to the very small total forested area.

Almost all the fires are human ignited. In LL fires are mainly ignited by arsonists (52%) and just 22% are involuntary, no lightning fires are recorded. Instead in mountain areas the arsonist incidence is much lower (36%) and lightning fires are 3% of the total (Figure 1.27, 1.28).

From 2005 to 2014 there are just 9 fires bigger than 10ha, listed in Table 1.1. In all cases the fires occurred during drought periods. Six of them spread fast because the main carries was represented by cured grass. The other two main spreading factors are the high slope and difficult terrain for the firefighters to access. Ground force intervention is limited on a steeply sloping mountainside where there are few roads and working in the forest could be difficult and dangerous. Scanno Cardovari fire is a particular case because it occurred on a very small island along the Adriatic coast and was very rapid, so it burned the whole island before intervention took place. Wind is not the main spread factor; it can act in two ways: drying the fuels in the days before the fire in 3 cases (foehn wind) or improving fire spread in 2 cases (strong wind). Six out to nine are surface fires and had FWI value between 8 and 16. Just one of the fires showed ground behaviour, it occurred whit FWI 13. The only crown fire is the La Muda one, which summarized the most dangerous conditions: high slope, foehn wind, a strong gusting wind and difficult access. It had a very high FWI value (32).

Table 1.1– Characteristics of the main fires bigger than 10 ha in the decade 2005-2014

				Spread factors				**Suppression limitations**		**Type of fire**			
Area	**Date**	**Name**	**burned area (ha)**	**tall grassland**	**high slope**	**strong wind**	**foehn wind**	**difficult access**	**night fire**	**crown**	**ground**	**surface**	**FWI**
MA	20/01/2007	Zaibena	14	x								x	8
MA	22/01/2012	Pizzoc	16	x					x				9
MA	24/01/2012	Camponi	18	x		x						x	11
MA	10/03/2012	Val Torra	24		x			x			x		13
MA	19/01/2007	M. Cielo	30		x		x	x				x	5
LL	26/09/2006	Cardovari	37	x				x				x	9
MA	25/01/2012	Costo	97	x	x							x	16
MA	10/05/2011	La Muda	270		x	x	x	x		x			32
MA	06/02/2011	San Mauro	312	x	x		x	x				x	11

Discussion

Italian Alpine regions and Switzerland showed a significant decrease in both number of fires and burned area from the 1990s to nowadays (Conedera 1996, Vacik *et al.* 2011, Valese *et al.* 2010, Valese *et al.* 2014, Zumbrunnen *et al.* 2011). Veneto Region follows this general trend, despite the high inter-annual variability.The decrease in burned area (Figures 8, 9), is more evident in MA while LL data show a relatively constant trend with some peaks probably due to protests against the institution of the Colli Euganei Regional Park (Masiero G., personal communication). From 1981 onwards the efficiency of the Regional firefighting system increased markedly in both prevention and suppression activities and this might be the main reason for the decrease in number of fires and burned area. Interviews with forest service and civil protection officials confirmed that, from 2000, when forest fire suppression duties moved from the National Forest Corps to the Regional Forest Service, there was a constant implementation of new equipment and suppression techniques. Probably after some years of adjustment the regional firefighting system reached full efficiency in about 2004.

Average burned area in MA is three times larger than in LL because the fuel is more continuous (i.e. forest cover is less fragmented) and mountain slopes are steeper (a condition that favours fire spread) Overall, the average burned area is similar to what is reported in the other Italian Alpine Regions (Valese 2011).

The fires behaviour and their seasonality differ between MA and LL. In LL the most severe fire season is during summer, but fires are relatively small because of the fuel discontinuity (land fragmentation) and also because the firefighting system is facilitated by a more accessible road network that allows a prompt tackling of the fire front. Both the Colli Euganei forests and coastal forests have a complex wild urban interface and a high natural value, so immediate fire suppression is required. A major concern is related to the camping areas often located in the sparse forests along the coast.

In MA, as reported in other Alpine regions (Valese *et al.* 2011), the main fire season is the winter. Indeed, summer precipitations are usually abundant but severe drought conditions can occur from January to April, especially on south-facing slopes where the snow cover melts quickly. Under these conditions fires might easily spread (up to 500-700 ha) because fuels are continuous and fuel load is relevant. Moreover the fragmented road network and steep slopes make an efficient fire suppression difficult.

Considering the whole region, the CDF of the burned area has a power-law distribution (Figure 19). This is similar to those reported in the literature (Reed and McKelvey 2002). Some reports (Malamud *et al.* 2005, Ricotta *et al.* 1999) suggested that the fire size/frequency relationship of bigger fires might follow a power law distribution, although this is not universally accepted (Reed and McKelvey 2002, Eastaugh and Vacik 2012). The fitted exponent (-1.69 considering the non-cumulated values) is within the range (from -1.3 to -1.81) of the distributions reported for fires in the US (Malamud *et al.* 2005).

The meaning of the exponent, slightly lower than -2, has still to be understood but it can be speculated that it might also be affected by the efficiency of the fire-suppression system (Doyle and Carlson 2000). Indeed, using the data of Malamud *et al.* (2005), we found a significant and negative correlation between the absolute slope of the CDF (e.g. 1.5) and the average burned area per single fire event (that can be considered a proxy for the efficiency of the firefighting system). The smaller the burned area per fire event the steeper the slope of the CDF, meaning that the frequency of medium-big fires decreases very rapidly compared to very small ones. Consistently with such a hypothesis, Malamud *et al.* (2005) found a steeper exponent in anthropogenic fires compared to lightning fires because the former are often in rural or more populated areas where fire suppression might be more effective compared to very remote areas. In the distribution of the fires in Veneto Region the exponent is towards the steepest values (-1.69), thus potentially indicating that the fire suppression system is relatively efficient.

The statistics show a clear change in burned area between the last decade and the two previous (Figure 1.23, 1.25). We therefore tested the hypothesis that the slope of the fires CDF might be affected by the efficiency of the firefighting system by comparing the CDF of the fires (>0.3 ha) in two different periods: before 2004 and from 2005 onwards. The slopes appeared markedly different (Figures 1.17, 1.18) with a steeper slope (-1.985) in the most recent years compared to previously (slope -1.637). This might be a quantitative indication that the efficiency of the actual suppression system has significantly improved compared to the past. Of course, the hypothesis must be further tested, by using more complete datasets, but the approach seems to be promising.

The distribution of fire types is similar in LL and in MA (Figure 20): the surface fires are by far the most common because the development towards more severe fires is prevented by the suppression activity and also because there are many winter fires in deciduous forests that cannot develop into crown fires. Crown fires are not very common but, as usual, they can be very severe (e.g. La Muda fire). Ground fires represent a very small part of the total, but they can be dangerous because they usually need a lot of effort to be suppressed.

The decreasing weight of forested compared with non-forested burned area (Figure 1.23) is mainly due to a strong decrease of coppice burned area (Figure 1.24, 1.25). This is probably connected to increasing suppression efficiency, as fires in broadleaved forests managed as coppice are usually quite easy to suppress. If in the past big fires could also occur in broadleaved forests, this kind of fire now never reaches an area larger than 10 ha.

In LL almost all the fires are human-caused. In LL arsonists are the main cause, probably because a higher population density also leads to a greater probability of conflicts among landowners and between landowners and political administrations (Figure 1.26). Thus, in the end, the denser population on the lowland hills and coasts has the final effect of increasing the fire ignition probability.

In MA accidental and natural causes are very rare. Arsonists are still the main ignition cause but to a lesser extent compared to LL. Ignition events are more related to farming than in the lowlands (Figure 1.27).

Lightning fires are rare but they can be problematic because they often occur in remote areas and can easily develop into ground fires. The percentage of lightning fires is lower than that reported in other parts of the Alps. In both Austria (18%)(Vacik *et al.* 2011) and Ticino (30%)(Conedera *et al.* 2006) the problem of lightning fires is an emergent issue.

Initial exploratory analysis suggests two distinct fire regimes corresponding to the periods 1985-2004 and 2005-2014. In the first period the number of fires and burned area slowly decreased and big fires occurred almost every year. From 2004 the burned area became very small and no big fires were recorded apart from in 2011 and 2012 when there were severe drought conditions. This might suggest (as already mentioned) that from the beginning of third millennium the fire suppression system of the Veneto Region achieved a fairly good efficiency. In ordinary conditions all fires are immediately suppressed, but in the case of drought and difficult environmental conditions limiting the suppression capacities (steep slopes, lack of roads, high amount of fine fuels, strong winds, night-time burning), large fires can still occur.

From 2005 to 2014, the fires larger than 10 ha were just the 0,017% of total fires (Table 2). In the most of cases they were fast surface fires, but sometime they develop into more extreme behaviours like crown fires (e.g. La Muda 2011) or they can also develop into ground fires (e.g. Val Torra 2012).

For all fires bigger than 10 ha, Table 1 reports the main limiting factors for an efficient suppression. The most dangerous condition is the concomitant occurrence of drought, land abandonment and steepness. This kind of fire is fast spreading and low intensity. They often almost self-extinguish with the night moisture. Observing big fires in the last 10 years, it seems that an FWI value between 8 to 16 is enough for big surface fires and crown fires are possible with FWI 32.

Conclusions

The Veneto Region has two different fire regimes: the LL fire regime that is more similar to the Mediterranean areas (i.e. fires during summer) and the MA fire regime with fires occurring mainly during the winter season.

In both areas, during the last thirty years, there has been a reduction in the number of fires and burned area, despite the increase in average air temperatures and more frequent and severe extreme weather conditions (Chiaudani 2008). This might be the result of the improvement in both prevention and suppression efficiency but other factors could also be involved, e.g. land use changes or social dynamics.

The power-law distribution of burned areas is affected by fire suppression efficiency and shows interesting potential application for efficiency evaluation.

The fire regime in Veneto Region, from the beginning of the third millennium to nowadays, is characterised by a state of “equilibrium” between fire ignitions and fire suppression capacity under not extreme conditions. The firefighting system seems to be able to cope with the “average” level of fire risk and in ordinary conditions all fires are suppressed within a few hours. However, the accumulation of fuels in the forest due to efficient fires suppression (i.e. the paradox of suppression) and the low timber exploitation, in addition to an underestimation of fire risk by the public and policymakers might all be factors increasing the probability of very severe fires in the future.

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Chapter II

Forest fuels classification in the Eastern Italian Alps

Introduction

A key challenge in modern wildfire mitigation and forest management is the accurate mapping of forest fuels in order to determine spatial fire hazard, plan mitigation efforts, and manage active fires (Krasnow *et al.* 2009). It is therefore extremely important to provide relevant accurate information on the amount and structure of plant fuels, and their susceptibility to burning. For this reason, the most advanced nations in the management of forest fires (such as Canada, USA, Australia) produced forest fuel maps providing data for landscape assessment, analysis and management.

The behaviour of a fire and its severity depend strongly on the type and amount of wildland fuel present, in addition to its state of dehydration. Wildland fuel is the dead and live biomass available for fire ignition and combustion (Albini 1976). Rothermel (1972) designed the fuel model concept to feed his semi-physical fire spread model with quantitative fuel data, considering four possible vectors for surface fire propagation (litter, herbs, shrubs, slash) and resulting in the original 13 Standard fire fuel models (Anderson 1982).

Most fire behaviour prediction systems developed for managers, for example, require fuel inputs to be represented by fire behavior fuel models, which have woody fuel components differentiated by particle diameter ranges (Anderson 1982, Scott and Burgan 2005).

Several studies developed photo guides and collections of Standard fire fuel models (Anderson 1982, Scott and Burgan 2005) and local fuel models (Cai *et al.* 2014, Cruz *et al.* 2008, Dimitrakopoulos and C 2002, Fernandes *et al.* 2006, Molina *et al.* 2011, Pierce *et al.* 2014). Standard fuel models that fit the main local vegetation characteristics can be used as input for fire spread modelling or in combination with custom fuel models when available (Arca *et al.* 2009, Boboulos *et al.* 2013, Duguy *et al.* 2007, Jahdi *et al.* 2015).

Direct harvesting techniques for estimating biomass are labour intensive and time consuming. The application of an allometric equation is a commonly used, non-destructive alternative in which biomass is estimated based on easily measured attributes of trees or shrubs (Sah *et al.* 2004). The most commonly used non-destructive technique is the one elaborated by (Brown et al. 1981).

Several surface fuel description systems are currently used by land management agencies in the Unites States, Europe, Canada and Australia, and most of them have the same categories, components and description variables (Sandberg *et al.* 2001, Scott and Burgan 2005). The main distinction between the existing fuel description systems is more in the approach used to create them rather than their accuracy, application and implementation in fire management (Keane 2013). There are three broad approaches for fuel description based on the processes used to develop the description: 1) association; 2) classification (direct or indirect); 3) abstraction (Keane 2013). In the association method, fuel information is assigned to categories in extant classifications. In the direct classification the fuel data are clustered into similar groups using statistical techniques. In indirect classification, unique fuelbeds are identified and sampled in the field and added as another category in the classification. Lastly, in the abstraction method fuel inputs to fire models are adjusted to match observed fire behaviour, and the adjusted fuel information becomes a category in the classification (Keane 2013).

The most commonly used method for producing fuel maps is the indirect method in which vegetation cover maps (often created with remotely sensed data) are used to create “crosswalks” to fuel characteristics (Keane *et al.* 2002, Stratton 2006). These methods are problematic because fuels are not always well correlated with vegetation type and the fine-scale variability of fuels within each polygon of similar vegetation is not accurately reflected (Krasnow *et al.* 2009).

In the Alps, we found some local studies on forest fuels, but no large-scale studies have been done until now and they have not yet been organized in a systematic quantitative analysis. The earliest study is on fuel load of *Pinus strobus* L. plantations in Piedmont Region (Camia 1994). Marchetti and Lozupone (1995) then used a fast sampling method for the attribution of Standard fuel models (Anderson 1982) in a large study area in Lombardy region. In 1995, Marchetti did a preliminary study on Vicenza province fuel models. He built 21 custom fuel models based on 650 surface fuel sampling plots taken with a fast method. The classification was supposed to be preparatory to creating a regional fuel map, unfortunately the map project never materialized and no details on the fuel sampling method were published. A data summary is published in Veneto Region fire prevention plan (Veneto 1999). In Piedmont Region fire prevention plan, a photo guide method was used to attribute a Standard fuel model to every forest type (Debrando *et al*. 2007). More recently, Ascoli *et al.* (2006) built a fuel model for prescribed burning on moors that has recently been upgraded (Ascoli *et al*. 2015). In Austria, a first effort in fuel classification was made in *Pinus* *sylvestris* L. forests (Arpaci *et al.* 2011). In the Lessinia area (Verona province), Goattin (2011) took 17 samples during the summer in mixed *Fraxinus ornus* L., *Ostrya Carpinifolia* Scop. and *Quercus pubescens* Willd. forests using Brown (1981). Dal Prà (2013) then sampled the same plots in January and February, which is a way to study the differences between summer and winter fuel load.

Despite the above studies, not enough data are available on forest fuel in the Eastern Alps for large-scale implementations of a fire behavior simulator.

The goals of this study are to characterize the most common forest fuel in the Eastern Italian Alps, to build some custom fuel models from the collected data and then to evaluate the problems connected to the different fuels classification methods.

Materials and methods

Study area

According to the two different fire regimes reported in chapter 1, Veneto region can be split in two parts: the Lowlands (LL), where fires occur mainly in summer and the Mountain areas (MA), where the fire season is in winter. Given the two different fire regimes we sampled in the two study areas separately. LL study area included the Colli Euganei hills and coastal forests. Fires in LL are always small, but because of the high population density, they have a high wild urban interface risk. MA study area included all the Prealpi and the southern part of Dolomites (Figure 2.1). In this area, the fires can be quite big and their behaviour is strongly dependent on orography.We did not include the northern part of Dolomites in the area because no big fires happened in the last 10 years, and because it has different climate and vegetation from the Prealpi and south Dolomites.

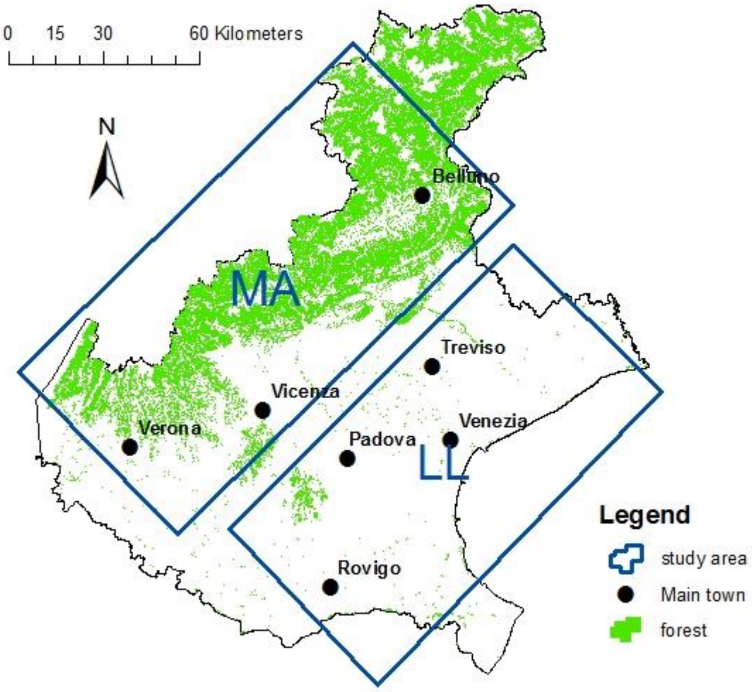


Figure 2.1 - Study areas

Geographic data

Veneto Region records data on forest fires in Veneto. The regional database contains information about fires from 1989 onwards. The information is the same as that recorded in the national forest statistical database managed by the National Forest Corps (Corpo Forestale dello Stato).

Veneto Region supplied the perimeters of burned areas from 2006 to 2014 in MA and from 2003 to 2014 in LL. We overlaid the land use map with the fire perimeters to find the most common forest type burned in the study areas.

In 2007 the Veneto Regional Administration produced a land use map covering the whole region. The map is based on photogrammetry and has a nominal scale of 1:10,000 (Veneto 2016). On the map, forests are classified according to very detailed local forest types classification (Del Favero *et al.* 2004, Del Favero 2006) based on the main forest species.

Forest types selection in the study areas

For resources optimization, we decided to sample only the forest types that are more useful for forest fire characterisation. Considering fire statistics, forest type distribution, and the most common fuels in the big fires, we selected:

- Hop hornbeam because this accounts for 27% of the burned area in MA and is widespread in the region (Table 1.1);
- Chestnut forest because this covers 40% of the burned area in LL and is quite common in the region (Table 1.1);
- Softwood plantation because this is among the most common forest types (Table 1.1) and mainly because it is potentially the most dangerous situation in the study area, in particular the *Pinus sylvestris* afforestation (e.g. La Muda fire 2012, chapter 3);
- Shrubland, abandoned pastures and farmland; this can include several species of deciduous shrubs and saplings of deciduous hardwood trees. We measured this kind of vegetation because it is the most commonly burned vegetation, in particular in the big fires (28% of regional burned area).

With the aim of better underhigh foresting the differences between fuels in MA and LL and between seasons, we sampled the same forest types in the two study areas. The main forest characteristics are reported in table 1.1, and illustrated in figures 1.2 to 1.17.

Table 1.1- Main forest characteristics

Forest types	Main tree species	Regional forest surface* (%)	Number of plots
Hop hornbeam	*Fraxinus ornus*, *Ostrya carpinifolia*, *Quercus pubescens*, *Robinia pseudoacacia* L. (LL) *Quercus ilex* L. (MA) *Quercus cerris* L., *Fagus sylvatica* L.	18.5	41
Chestnut	*Castanea sativa* Mill., *Robinia pseudoacacia*, *Fraxinus ornus*, *Ostrya carpinifolia*, *Quercus pubescens. (*MA) *Quercus cerris.*	4.9	31
Softwood plantations	(LL) *Pinus nigra* Arn., *Pinus pinaster* Aiton, *Pinus pinea* L. (MA) *Pinus sylvestris*, *Picea abies* Kars., *Larix decidua* Mill.	7.4	29
Shrubland	*Fraxinus ornus*, *Ostrya carpinifolia*, *Quercus pubescens.* (MA) *Corylus avellana* L., *Fagus sylvatica*	2.3	22

*(Del Favero 2006)

Figure 2.2– LL – Chestnut high forest

Figure 2.3– LL – Chestnut coppice

Figure 2.4– LL – Hop hornbeam coppice

Figure 2.5– LL – Hop hornbeam coppice

Figure 2.6– LL – Dense Shrubland

Figure 2.7– LL – Low density Shrubland

Figure 2.8– LL – Softwood plantation

Figure 2.9– LL – Softwood plantation

Figure 2.10– MA – Chestnut high forest

Figure 2.11– MA – Chestnut coppice

Figure 2.12– MA – Hop hornbeam coppice

Figure 2.13– MA – Hop hornbeam coppice

Figure 2.14– MA – Dense shrubland

Figure 2.15– MA – Low density shrubland

Figure 2.16– MA – Softwood high forest

Figure 2.17– MA – Softwood high forest

Sampling distribution

In 2013, we did two different sampling distributions for LL and MA areas. In order to better represent the fuel condition in the areas commonly burned, all samples were randomly located close to where fires happened in recent years.

In MA, we mapped the fires that happened from 2006 to 2012 using data collected by Veneto Region Forest Service. Using ArcGIS, we created a 200 m buffer area around the fires with a burned area no smaller than 5000 m^2. We then overlaid the buffer area on the regional land use map (Veneto 2016). From the resulting map, we extracted the areas covered by the selected forest types.

In LL, we mapped the fires that happened from 2003 to 2012. Using ArcGIS, we created a 400m buffer area around the fires with a burned area no smaller than 1,000 m^2. We then overlaid the buffer area on the regional land use map (Veneto 2016). We had to take into consideration a longer years series, select smaller fires and create a larger buffer area than in the MA area because most fires in LL are very small. From the resulting map, we extracted the areas covered by the selected forest types. Then, in the selected areas, we randomly distributed 60 sampling plots for every forest type using ArcGIS "spatial ecology" extension. We fixed 50 m as the minimum distance between samples.

Designed sampling plots outnumbered the plots effectively needed in order to have spares in case some plots could not be sampled for any reason. In both study areas, we sampled until the 1H fuels had at least a percentage error lower than 20%, as suggested in Brown (1981).

In the forest, we used GPS to find sampling positions in the field. When we could not reach a designed sampling plot, mainly because of fenced private property or a very steep slope, we sampled in the closest reachable site if a studied forest type was available, otherwise we just deleted the plot from the list. In some cases, the real forest type in the sampling plot differed from that reported on the land use map. In this case, if the forest type was a studied one, we sampled anyway. Otherwise, we deleted the plot.

In LL, we sampled 61 plots from June to September in 2013 and 2014. In MA, we sampled 46 plots from January to April in 2014 and 2015. In MA, we also used the 16 plots data collected by Dal Prà (2013) since they were collected with the same method and in the same season as ours. In the whole region, 107 plots are available for the study.

Sampling method

The Brown *et al.* (1981) sampling method was used. We made some minor adjustments to highlight the wide variability in fuel distribution. We measured all the surface fuels that are common inputs to fire models (Table 2). Plot design is reported in Figure 1.18.

We measured the ground dead wood using the linear intersect method (Brown *et al.* 1981): 1H wood load was measured along 3 micro transects of 70 cm located at two ends and at the centre of the main 20 m transect. 10H wood load was measured along three micro transects of 100 cm located at two extremes and at the centre of the 20 m transect. 100H and 1000H were measured along the whole 20 m transect. We classified 100H and 1000H in two categories: sound and rotten.

We then collected litter and herbs in four 40x70 cm rectangles, located along the sampling plane, oven dried the samples at 100 °C for 48h and weighed them. We visually estimated the dead grass percentage on site.

We measured the number of stems, diameter and height of all shrubs less than 3 m tall, in two circles of 100 cm diameter. We also visually estimated the percentage of dead wood In every shrub.

Lastly, we measured duff-organic soil layer and litter depth in four points along the sampling area, one every 150 cm.

We considered the fuels with a surface cover > 30% as influent for fire propagation, so we counted their height in the fuelbed height measure.

In the sampling plots, we also measured the main forest parameters (slope, canopy cover, amount of dead trees, main species) and some canopy fuel characteristics (trees height, trees base height).

We determined canopy closure by taking three photos of the sky at both ends and in the centre of the sampling area. We then elaborated the photos in ImmageJ to measure the sky percentage. In the plots sampled in winter, photos show the winter canopy closure. The summer canopy closure could only be supposed by visual estimation. We estimated the tree average height by measuring three average trees in every plot using an Ipsometer. We then measured high forest basal area with a Bitterlich relascope. Lastly, we visually estimated shrub and grass cover, and high foresting dead trees. We took 19 photos in every plot following a Standard protocol.

Table 1.2- Description of surface fuel components sampled in this study, modified from Keane *et al*. (2012).

Fuel component	**Fuel component variable**	**Common name**	**Size**	**description**
Ground dead wood	1H	Twigs	<1cm diameter	Woody fuels that are disconnected from parent plants and lying on the fuelbed within 2 m of the ground.
	10H	Branches	1-2.5 cm diameter	
	100H	Large branches	2.5-7 cm diameter	
	1000H	Logs	7+ cm diameter	
Shrubs	Shrubs	Shrubby	All shrubby material less than 3 m tall	All burnable shrubby biomass less than 3 m tall
Herbaceous	Herbs	Herbs	All sizes	All live and dead grass, forbs, and fern biomass
Duff	Duff	Duff	All sizes	Partially decomposed biomass whose origins cannot be determined
Litter	Litter	Litter	All sizes excluding woody	

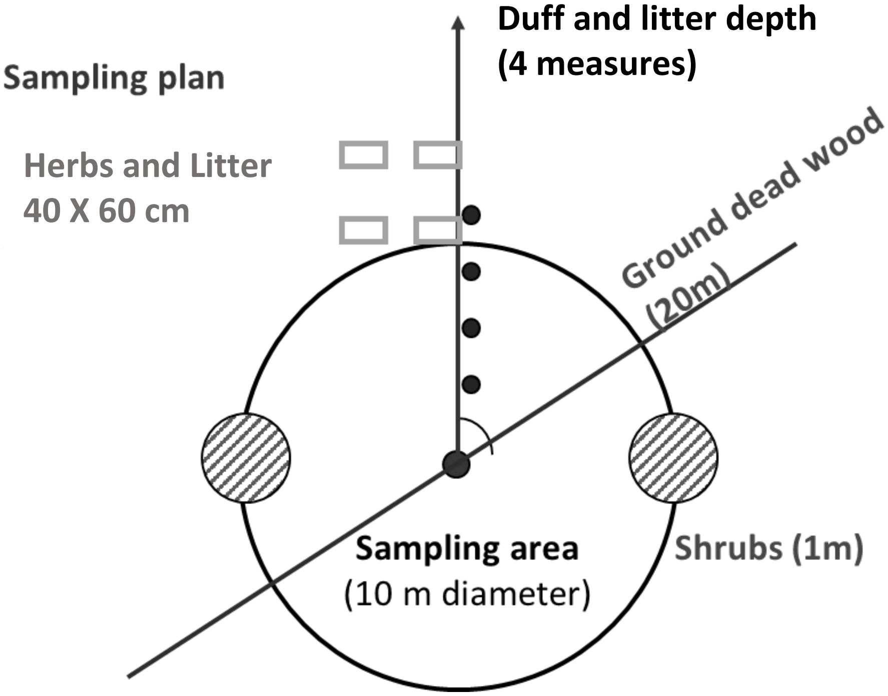


Figure 2.18 - Plot design (Goatin 2011)

Surface fuel loading calculation

For surface fuel loading calculation, we used the formulas reported in *Fuel and Fire effects monitoring guide* (Anderson *et al*. 2006).

- 1H and 10H dead wood are calculated as follows:

$$M = \left[\frac{1.22nd^2sca}{L}\right] * 0.8 * 10{,}000 \quad (1)$$

M = dead wood load, t ha^{-1};

1.22 = constant;

n = number of pieces crossing the transect

d^2 = average square diameter of measured pieces, m^2;

s = wood bulk density, t m^{-3}; we used the bulk density of the main species from Giordano (1976)

c = slope correction factor (Table 3);

Table 2.3- Slope correction factor

Slope (%)	0	10	20	30	40	50	60	70	80	90	100	110
Correction factor *c*	1.00	1.00	1.02	1.04	1.08	1.12	1.17	1.22	1.28	1.35	1.41	1.49

a = angle correction factor (1.13);

L = transect length, m;

0.8= decay value (Woodall *et al.* 2008)

10,000 = conversion factor from m^2 to hectare.

- 100H and 1000H are calculated as follows:

$$M = \left[\frac{1.22s\sum di^2 * ca}{L}\right] * 10{,}000 \qquad (2)$$

di^2 = square diameter of every piece, m^2;

s = wood bulk density, t m^{-3}; we used the bulk density of the main species from Giordano (1976)

c = slope correction factor (Table 3);

a = angle correction factor (1.13);

In the case of rotten wood the wood load was reduced by a factor of 0.45 for softwood and 0.42 for hardwood (Waddell 2002)

- The duff-organic soil loading for the duff-organic layer (kg m^{-2}) is calculated as:

$$M = \frac{3.63Bd}{2.54 * 0.4} \qquad (3)$$

M= duff-organic soil load (t ha^{-1});

3.63 = constant;

B = bulk density (lb.ft^{-3}). Duff-organic soil bulk density was obtained from the literature (Woodall *et al.* 2008);

d = average duff-organic soil depth, cm;

2.54 * 0.4 = conversion factor from lb. acre^{-1} to t ha^{-1}.

- We oven dried grass and litter separately at 105 °C for 48 hours. We then used the following formula to obtain the load per hectare:

$$M = \frac{mc10{,}000}{0.18} / 100{,}000 \qquad (4)$$

M = grass or litter load, t ha^{-1};
c = slope correction factor (Table 3);
m = grass or litter oven dry weight.

- Shrubs loading was calculated by summing the weight of individual stems by species:

$$M = \frac{8.8185\ c\ n\ w}{3.14 * 0.4} * 0.000454 \qquad (5)$$

M = shrub load, mg ha^{-1};

8.8185 = constant;

c = slope correction factor;

n = number of stems;

w = aboveground weight of shrubs per stem (gr);

0.000454 = conversion factor from lb. acre^{-1} to mg ha^{-1}.

The shrubs aboveground weight (w) was estimated using the aboveground weight of shrubs per diameter class reported in Brown (1984). For every shrub found in the sampling plots, we gave the weight of the most similar shrub reported in Brown (1984), separated by diameter classes.

In every plot we determined the fuelbed height calculating the average between the height of the ground fuel components with more than 30% cover, since 30% is reported in the Prometheus project classification (Giakoumakis *et al.* 2002, Riano *et al.* 2003) as threshold for fuel model separation.

Forest fuel models classification

A fuel model is a set of fuelbed inputs needed by a particular fire behaviour or fire effects model (Scott and Burgan 2005). Although a fuel model technically includes all fuel inputs to the Rothermel's surface fire spread model, several fuel inputs have never been subject to control by a user when creating fuel models. The fuel model inputs that vary among models are (Scott and Burgan 2005):

- fuel load by size class and category;
- live woody, live herbaceous, and dead 1H surface area to volume ratio (SAV)
- Fuelbed depth
- Dead fuel extinction moisture content
- Heat content of live and dead fuels

Based on the collected data we built some custom fuel models. In all models, we used the median values of fuel load and fuelbed. The median is more suitable for model building (Bovio and Ascoli 2013), since fuels distribution was not normal and, furthermore, the average values are often too high for a correct fire simulation. In our custom fuel models, 1H fuels included 1H ground dead wood and litter.

Surface to volume ration (S/V) was based on literature data. Unfortunately, very few data are available for most of the hardwood species in the study. Hernando (2008) gave some values for *Castanea sativa.* More information is available on pine species (Brown 1970, Camia 1994, Hernando *et al.* 2008). We gave every custom fuel model the same S/V value as the most similar Standard fuel model (Scott and Burgan 2005). The extinction moisture was also assigned based on the most similar Standard fuel model (Scott and Burgan 2005). Litter fuel models, were given 25%, understory fuel model, 20% and grass fuel models 15%. Live and dead fuel heat content was fixed at 18608 KJ/kg as in the Standard fire fuel models (Anderson 1982, Scott and Burgan 2005)

We tested three different ways to aggregate fuel data for creating fuel models: association based on forest types; direct classification based on forest structure and direct classification with cluster analysis (Keane 2013). In the association method, fuels information is assigned to categories in extant classifications. In the direct classification the fuel data are clustered into similar groups using statistical techniques (Keane 2013). Due to the different origin and environmental conditions, we did not mix data collected in MA in winter and in LL in summer. We created separate fuel models for the two study areas.

<u>Forest type classification</u> - Using the association method (Keane 2013), fuel data collected in the sampling plots were summarized based on the forest type (Del Favero 2006) recorded in the plots (Table 1). In addition to forest type models we created a model for grassland in MA using the data of all the plots where grass was the main fuel.

<u>Prometheus classification</u> - These fuel types were defined for surface fire modelling, taking into account fuel height and density. The main classification criteria is the propagation element, divided into three major groups: grass, shrubs, or ground litter. The Prometheus system is based mainly on type and height of propagation elements, and it comprises seven fuel types reported in Figure 2.19 (Giakoumakis *et al.* 2002, Riano *et al.* 2003).

We classified each plot with the Prometheus classification and then aggregated all plots having the same class.

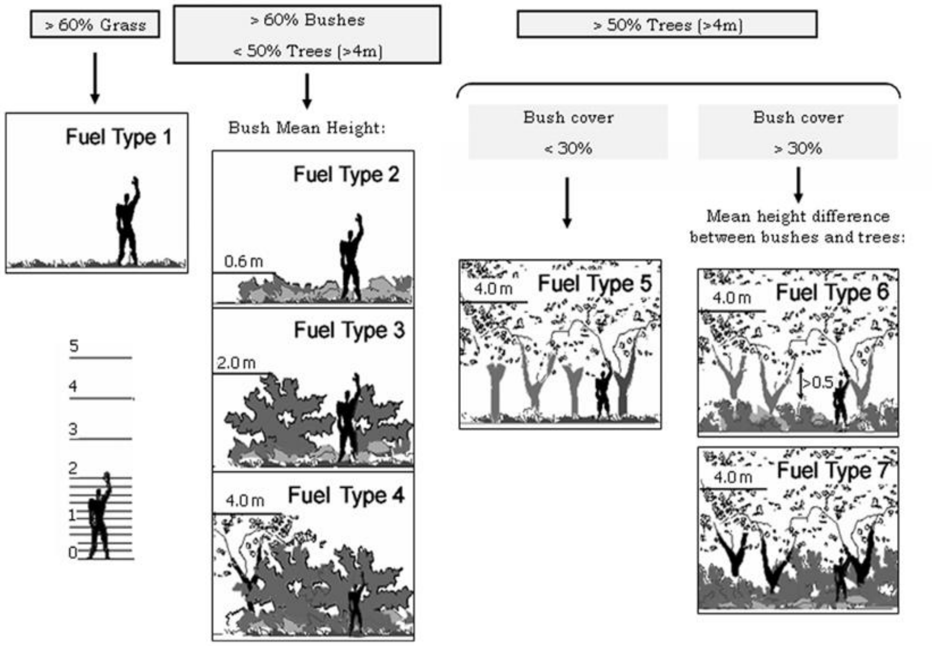


Figure 2.19 -Prometheus classification

Cluster classification–The dataset was subjected to cluster analysis with the aim of identifying homogeneous groups in terms of fuel load (1H, 10H, 100H, live herbs, live shrubs) and fuelbed height. The cluster analysis classifies a set of observations into several mutually exclusive unknown groups based on combination of interval variables. The term cluster analysis (first used by Tryon in1939) encompasses a number of different algorithms and methods for grouping objects of a similar kind into respective categories. In this work, the Ward method was used because it is particularly suitable for minimizing the variance within groups. The distance used was the Euclidean; the geometric distance in multidimensional space. Clustering was performed using Infostat®.

Data analysis

Since the data do not have a normal distribution, we used the Wilcoxon (Mann-Whitney U) (Conover and Iman 1981) non-parametric test to compare two-sample inference. It can be applied on unknown distributions (6).

$$W° = \frac{W-E(W)}{S(W)} \quad (6)$$

Where: $$E(W) = (\frac{n(1)(n(2)+n(1)+1)}{2}) \quad (7)$$

and $$S(W) = \sqrt{\frac{n(1)n(2)(n(2)+n(1)+1)}{12}} \quad (8)$$

Because of non-normal distribution, we used Kruskal-Wallis non-parametric tests (Kruskal and Wallis 1952) when we had to compare more than two populations. It is used for comparing two or more samples that are independent, and that may have different sample sizes. Since it is a non-parametric method, the Kruskal–Wallis test does not assume a normal distribution of the residuals, unlike the analogous one-way analysis of variance. If the researcher can make the more stringent assumptions of an identically shaped and scaled distribution for all groups, except for any difference in medians, then the null hypothesis is that the medians of all groups are equal. The alternative hypothesis is that at least one population median of one group is different from the population median of at least one other group. The test statistic is given by:

$$K=(N\text{-}1)\frac{\sum_{i=1}^{g} n_i(\overline{r_{i\cdot}}-\bar{r})^2}{\sum_{i=1}^{g}\sum_{j=1}^{n_i}\left(r_{ij}-\bar{r}\right)^2} \qquad (9)$$

Where:

- n_i is the number of observations in group *i*
- r_{ij} is the rank (among all observations) of observation *j* from group *i*
- *N* is the total number of observations across all groups
- $\overline{r_{i\cdot}} = \frac{\sum_{j=1}^{n_i} r_{ij}}{n_i}$ (10)
- $\bar{r} = \frac{1}{2}(N+1)$ is the average of all the r_{ij} (11)

We used the cumulative density function (CDF) to analyse fuel distribution (Zwillinger and Kokoska 1999). In probability theory and statistics, the CDF describes the probability that a real-valued random variable X with a given probability distribution will be found to have a value less than or equal to x. In the case of a continuous distribution, it gives the area under the probability density function from minus infinity to x. The cumulative distribution function of a real-valued random variable X is the function given by:

$$F_x(x) = P(X \leq x) \qquad (12)$$

Where the right-hand side represents the probability that the random variable X takes on a value less than or equal to x. The probability that X lies in the semi-closed interval (a, b), where a < b, is therefore:

$$P(a < X \leq b) = F_x(b) - F_x(a) \qquad (13)$$

Correlations were explored with the Spearman correlation coefficient (Conover, 1999). This is a non-parametric measure of association based on ranks, which can be used for discrete or continuous variables not necessarily normal.

Statistics were performed using Infostat ®.

Results

Fuel characteristics

The data collection allowed ten forest fuel components to be characterized in four vegetation associations based on two study areas. The combinations between the different high forest areas and different vegetation associations resulted in eight different forest ecosystems for the study area. The main forest characteristics are given in Table 2.4 and Table 2.5.

In LL study area, chestnut forests (*Castanea sativa)* were managed as coppice (9 plots) or they were in conversion to high forest (10 plots) for natural reasons. Because of several phytosanitary problems that are quite common in Alpine chestnut forests (e.g. ring shake defect and chestnut blight disease) (Bounous 2002), the plots had quite a lot of dead trees (15%) and coarse dead wood. 6 plots were semi pure forest. In all the other plots, chestnut was mixed with *Fraxinus ornus, Quercus pubescens* and *Robinia Pseudoacacia*. Shrub cover was often high in coppices and low in high forests. The main shrubs were *Rubus* spp., L. and *Ruscus aculeatus* L. Grass cover was generally very low, apart from in former chestnut production forests. Undergrowth distribution was very irregular. The most common fuelbeds were litter and shrubs.

The hop hornbeam forest (*Fraxinus ornus, Ostrya carpinifolia* and *Quercus pubescens*) was commonly coppiced (12 plots) and several plots were very young. Density was rarely high, so the forest was very rich in undergrowth (*Ruscus aculeatus*, *Asparagus acutifolius* L., *Ligustrum vulgare* L., *Crataegus monogyna* Jacq.) and young saplings. Grass cover was very variable. Fuelbed was mainly represented by litter and shrubs.

Softwood plantations were mainly composed of *Pinus pinaster* and some *Pinus pinea* along the coast and of *Pinus nigra* in the Colli Euganei, other exotic softwoods were sometimes found. In 10 plots, the forest was very dense and there was no undergrowth but only a thick litter layer. In the lower density forest, the undergrowth was mainly formed of: *Rubus ssp. Asparagus acutifolius, Ligustrum vulgare* and hardwood saplings (*Quercus ilex, Ostrya carpinifolia, Fraxinus ornus, Robinia pseudoacacia*). Fuelbed was generally just litter and in some cases litter and shrubs.

Shrublands were abandoned pastures or farmland under spontaneous afforestation. Trees were usually young and small, apart from some scattered old trees already on site before the abandonment.

Shrubs were mainly saplings of *Fraxinus ornus, Ostrya carpinifolia, Quercus pubescens, Robinia pseudoacacia* and some local shrubs e.g. *Crataegus monogyna, Cotinus coggygria* Scopp. and *Ligustrum vulgare*. Herbs cover was always higher than 30% and mainly composed of grasses. Fuelbed was generally a mix of shrubs and grass.

In MA study area, the chestnut forest was generally older and healthier than in LL and had fewer dead trees. Four plots were in former chestnut production forest now abandoned; in these cases *Robinia pseudoacacia* became the dominant species. Shrub cover was very variable according to management method and, apart from in old high forests, it was quite high. The main shrub species was *Rubus* spp. The fuelbed was composed of litter and low shrubs.

The hop hornbeam forest was commonly managed as coppice (18 plots), but in some cases they were managed or unmanaged high forests. There were few dead trees and the average tree height and diameter was higher than in the LL. Shrub cover was lower than in LL (33%) and the main species were *Rubus* spp. and *Corylus avellana*, tree saplings were very common. The fuelbed was composed mainly of litter and in some cases shrubs.

Softwood plantations were very varied in species because, between the 1940s and 1980s, there were several experiments of planting softwoods out of their habitat. *Picea abies* mixed with *Larix decidua* and *Pinus nigra* dominated five plots. *Pinus sylvestris* was the main species in four and one plot was a mix of local and exotic softwoods: *Picea abies, Cedrus deodara, Pinus strobo* etc. Tree density was very high in most cases because these kinds of plantation do not have economic value and are often unmanaged. Due to high density and because they were planted out of their natural habitat, they often had a thick litter layer, apart from when the slope was very steep. Just three plots had shrub cover over 30%. Shrubs were mainly saplings of spontaneous hardwoods: *Ostrya carpinifolia* and *Fraxinus ornus. Rubus* spp. and *Corylus avellana* were also common. Thick litter composed the fuelbed.

The shrubland reported in the forest map included two very different situations: *Corylus avellana* coppice and abandoned pastures under spontaneous afforestation. In the *Corylus avellana* coppice the fuelbed was mainly light litter. Shrub and grass cover was very low. The forest was almost pure. In the abandoned pastures, grass cover was very high, tree cover and shrub cover was usually less than 40%. The main species were *Ostrya carpinifolia, Fraxinus ornus, Quercus pubescens, Corylus avellana* and *Rubus* spp. Fuelbed height depended mainly on grass.

Table 2.4 -Plot management

Study area	Sampling campaign	Forest type	Coppicing (n)	High forest (n)	Unmanaged (n)
LL	January - April	chestnut	9	10	
		hop hornbeam	12	4	
		shrubland			7
		softwoods plantation		19	
MA	June - September	chestnut	5	3	4
		hop hornbeam	18	3	4
		shrubland	6		9
		softwoods plantation		10	

Table 2.5 -Main forest characteristics (average)

Study area	Forest type	Dead trees (%)	Canopy closure (%)	Shrubs cover (%)	Herbs cover (%)	Trees diameter (m)	Trees height (m)	Basal area (m^{2}ha^{-1})
LL	chestnut	16	77	39	18	0.15	12	27.2
	hop hornbeam	7	65	58	37	0.12	11	18.2
	shrubland	6	62	66	48	0.06	6	9.1
	softwoods plantation	3	68	37	27	0.28	13	21.0
MA	chestnut	3	65	44	12	0.24	17	22.5
	hop hornbeam	3	63	31	20	0.20	12	16.8
	shrubland	4	46	32	60	0.09	6	9.9
	softwoods plantation	2	68	21	44	0.25	17	25.4

Fuel load

Fuel load parameters are given in Tables 2.6 and 2.7 and in Figures 2.20 – 2.22.

In LL, chestnut and hop hornbeam forests did not show any significant difference in fuel load (Wilcoxon), so they could be considered as a unique class. They had quite a lot of fine coarse dead wood (1.42 and 1.02 t ha^{-1} respectively), litter (3.40 and 2.63 t ha^{-1}) and shrubs (3.52 t ha^{-1} and 3.88 t ha^{-1}). Fuelbed in chestnut (0.33 cm) was lower than in hop hornbeam (0.45 cm)

Shrubland was mainly rich in shrubs (5.50 t ha^{-1}) and had a lot of 10H dead wood (4.08 t ha^{-1}) and very little 1H, 100H and 1000H. Fuelbed was high (0.56 cm).

Softwood plantations had a very thick layer of litter (8.65 t ha^{-1}) and duff-organic soil (63.07 t ha^{-1}). 1H was similar to the other forest types (1.25 t ha^{-1}) and the same for shrubs (2.17 t ha^{-1}). Fuelbed was quite low (0.24 cm).

The fine ground dead wood (1H) did not show important differences between forest types. 100H dead wood had similar load in chestnut and hop hornbeam forests and very low load in shrubland and softwoods. 1000H had a high mean load in chestnut forest (6.66 t ha^{-1}) and low or null load in the other forest types (Table 2.6). Herbs had a low load in all the forest types. The amount of shrubs in softwoods was lower than in the other forest types because of the high density of softwood plantation.

In MA, the litter load was higher in the hardwoods and lower in the softwoods compared with the LL ones. Like in LL, in MA study area the differences in fuel load between chestnut and hop hornbeam were not significant (Wilcoxon). Both categories were rich in 10H (5.13 and 5.66 t ha^{-1}), litter (4.20 and 4.56 t ha^{-1}) and duff-organic soil (36,00 and 41.37 t ha^{-1}). Shrubs had a low fuel load in the most of plots. The fuelbed was 0.32 cm in chestnut and 0.19 cm in hop hornbeam.

Shrubland was rich in herbs (1.75 t ha^{-1}), litter (3.69 t ha^{-1}) and 10H (4.08 t ha^{-1}). In shrubland, the amount of shrubs was also low because most shrubs do not have leaves in winter.

Softwood plantations had thick litter layer (6.04 t ha^{-1}) and a higher duff-organic soil load than the other forest types (58.41 t ha^{-1}), but lower than the plantations located in LL. Fine dead wood was higher than in the other forest types (2.00 t ha^{-1}). Coarse dead wood, grass and shrubs had a very low load, so the fuelbed was low (0.11 cm) (Figure 2.20).

The duff-organic soil had a very high fuel load in softwood plantations, due to a thick layer of undecomposed needles found in several plots (Table 2.7).

Table 2.6– LL - Main fuel parameters

Forest type	Variable	Mean	Median	S.D.	Minimum	Maximum
Chestnut	1h (t ha^{-1})	1.42	1.21	1.02	0.27	4.82
	10h (t ha^{-1})	6.68	7.02	3.62	1.61	12.35
	100h (t ha^{-1})	2.23	0.88	2.76	0.00	8.68
	1000h (t ha^{-1})	6.60	0.00	13.85	0.00	46.16
	herbs (t ha^{-1})	0.14	0.02	0.25	0.00	1.00
	litter (t ha^{-1})	3.40	3.65	1.59	0.58	6.04
	duff* (t ha^{-1})	44.87	36.96	34.73	0.00	120.14
	shrubs (t ha^{-1})	3.52	2.33	3.53	0.40	13.74
	fuelbed (m)	0.33	0.28	0.23	0.02	0.86
Hop hornbeam	1h (t ha^{-1})	2.02	1.64	1.47	0.26	5.41
	10h (t ha^{-1})	6.81	6.07	4.23	0.72	14.39
	100h (t ha^{-1})	2.54	0.29	4.78	0.00	14.45
	1000h (t ha^{-1})	1.47	0.00	2.85	0.00	9.85
	herbs (t ha^{-1})	0.57	0.09	0.91	0.00	3.20
	litter (t ha^{-1})	2.63	2.24	1.48	0.85	6.44
	duff* (t ha^{-1})	30.03	23.10	24.98	2.31	73.93
	shrubs (t ha^{-1})	3.88	2.80	4.58	0.00	17.74
	fuelbed (m)	0.45	0.39	0.31	0.01	1.15
Shrubland	1h (t ha^{-1})	0.82	0.76	0.40	0.32	1.35
	10h (t ha^{-1})	5.21	1.98	6.55	0.00	18.23
	100h (t ha^{-1})	0.10	0.00	0.26	0.00	0.70
	1000h (t ha^{-1})	1.74	0.00	4.61	0.00	12.20
	herbs (t ha^{-1})	0.77	0.41	0.80	0.00	1.82
	litter (t ha^{-1})	1.85	1.40	1.17	0.81	4.14
	duff* (t ha^{-1})	36.96	21.30	11.55	64.69	32.34
	shrubs (t ha^{-1})	5.50	2.94	4.88	1.34	14.85
	fuelbed (m)	0.56	0.61	0.28	0.06	0.89
Softwoods	1h (t ha^{-1})	1.25	0.90	1.38	0.17	6.45
	10h (t ha^{-1})	3.38	2.24	4.04	0.00	16.94
	100h (t ha^{-1})	0.39	0.00	0.67	0.00	2.26
	1000h (t ha^{-1})	0.00	0.00	0.00	0.00	0.00
	herbs (t ha^{-1})	0.66	0.22	1.12	0.00	4.78
	litter (t ha^{-1})	8.65	8.27	5.12	0.00	17.44
	duff* (t ha^{-1})	63.07	55.17	41.91	3.45	168.97
	shrubs (t ha^{-1})	2.17	0.75	3.91	0.00	16.17
	fuelbed (m)	0.24	0.14	0.23	0.04	0.82

Table 2.7– MA - Main fuel parameters

Forest type	Variable	Mean	Median	S.D.	Minimum	Maximum
Chestnut	1h (t ha^{-1})	1.20	1.02	0.76	0.37	3.02
	10h (t ha^{-1})	5.66	4.36	3.84	1.39	13.62
	100h (t ha^{-1})	0.35	0.29	0.31	0.00	0.94
	1000h (t ha^{-1})	0.00	0.00	0.00	0.00	0.00
	herbs (t ha^{-1})	0.21	0.10	0.37	0.00	1.35
	litter (t ha^{-1})	4.20	3.27	2.66	1.73	10.67
	duff* (t ha^{-1})	36.00	35.73	6.93	117.83	15.02
	shrubs (t ha^{-1})	0.64	0.41	0.71	0.00	2.09
	fuelbed (m)	0.32	0.16	0.36	0.01	0.94
Hop hornbeam	1h (t ha^{-1})	1.86	1.52	1.36	0.22	4.85
	10h (t ha^{-1})	5.13	3.72	5.64	0.34	22.83
	100h (t ha^{-1})	0.91	0.27	1.33	0.00	4.85
	1000h (t ha^{-1})	0.95	0.00	3.19	0.00	15.38
	herbs (t ha^{-1})	0.44	0.00	1.02	0.00	4.88
	litter (t ha^{-1})	4.56	4.53	1.45	2.26	8.01
	duff* (t ha^{-1})	41.37	48.86	3.23	194.07	20.79
	shrubs (t ha^{-1})	0.81	0.00	1.71	0.00	6.74
	fuelbed (m)	0.19	0.07	0.28	0.01	1.31
Shrubland	1h (t ha^{-1})	1.33	0.97	1.13	0.00	3.23
	10h (t ha^{-1})	4.08	2.08	5.47	0.00	18.07
	100h (t ha^{-1})	0.54	0.00	1.07	0.00	3.70
	1000h (t ha^{-1})	0.00	0.00	0.00	0.00	0.00
	herbs (t ha^{-1})	1.75	0.93	2.15	0.00	6.30
	litter (t ha^{-1})	3.69	3.33	3.04	0.00	13.29
	duff* (t ha^{-1})	48.05	16.17	53.67	4.62	166.34
	shrubs (t ha^{-1})	0.78	0.00	2.10	0.00	8.22
	fuelbed (m)	0.13	0.14	0.10	0.02	0.40
Softwoods	1h (t ha^{-1})	2.00	1.57	1.26	0.26	4.51
	10h (t ha^{-1})	3.47	2.61	3.32	0.00	11.24
	100h (t ha^{-1})	0.66	0.13	0.91	0.00	2.47
	1000h (t ha^{-1})	1.46	0.00	2.52	0.00	7.17
	herbs (t ha^{-1})	0.56	0.32	0.63	0.00	1.74
	litter (t ha^{-1})	6.04	5.89	2.47	2.61	10.84
	duff* (t ha^{-1})	58.41	55.17	32.72	20.06	124.14
	shrubs (t ha^{-1})	0.16	0.04	0.27	0.00	0.81
	fuelbed (m)	0.11	0.10	0.06	0.03	0.20

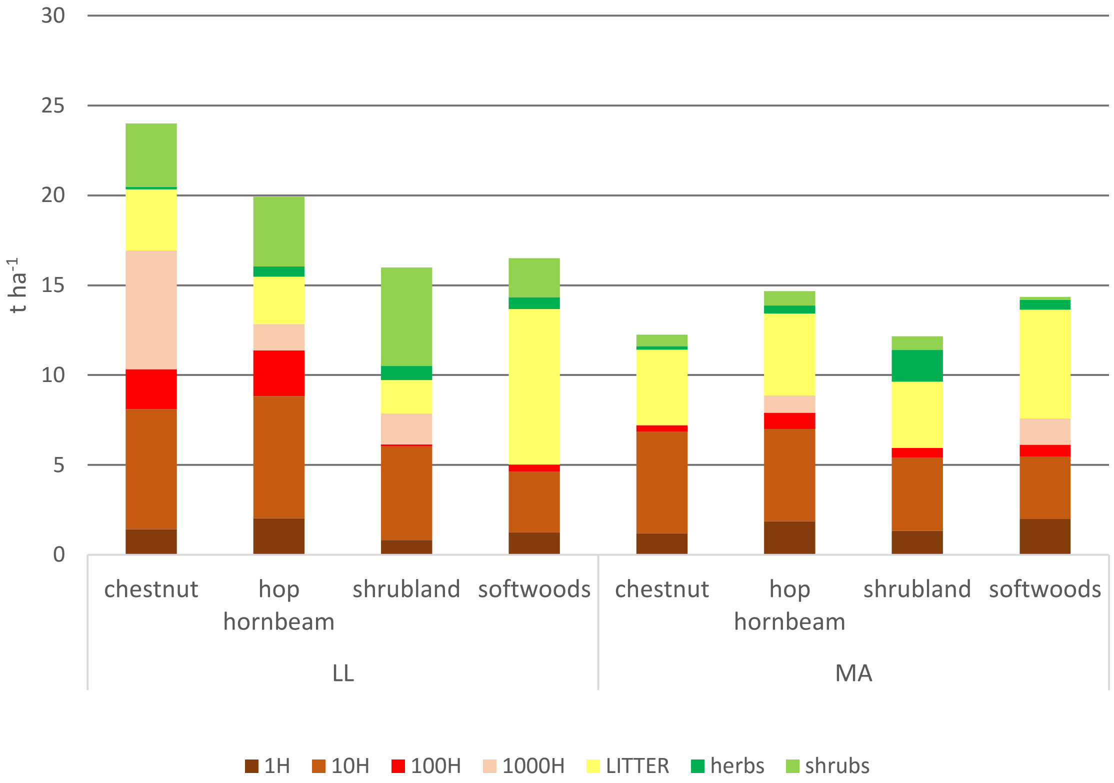
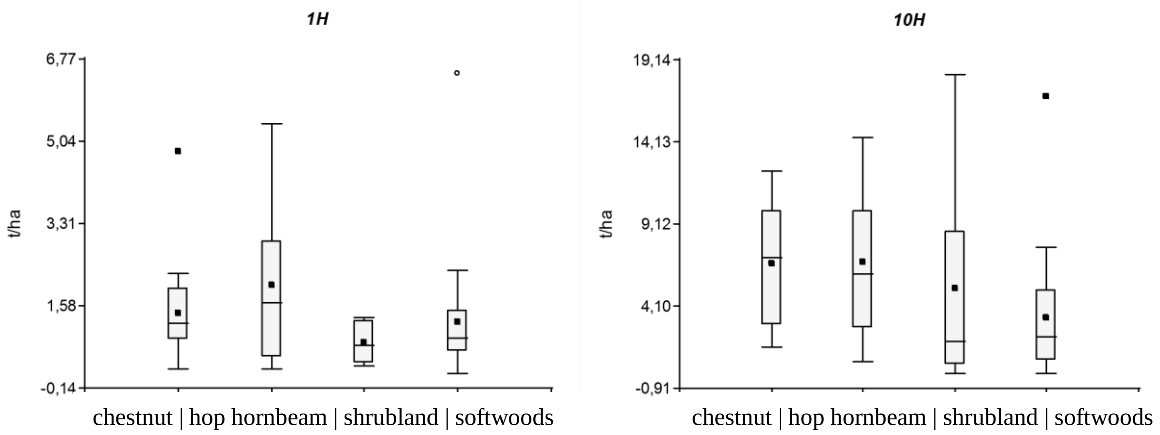


Figure 2.20– Total fuel load per forest type and study area (t ha^{-1})



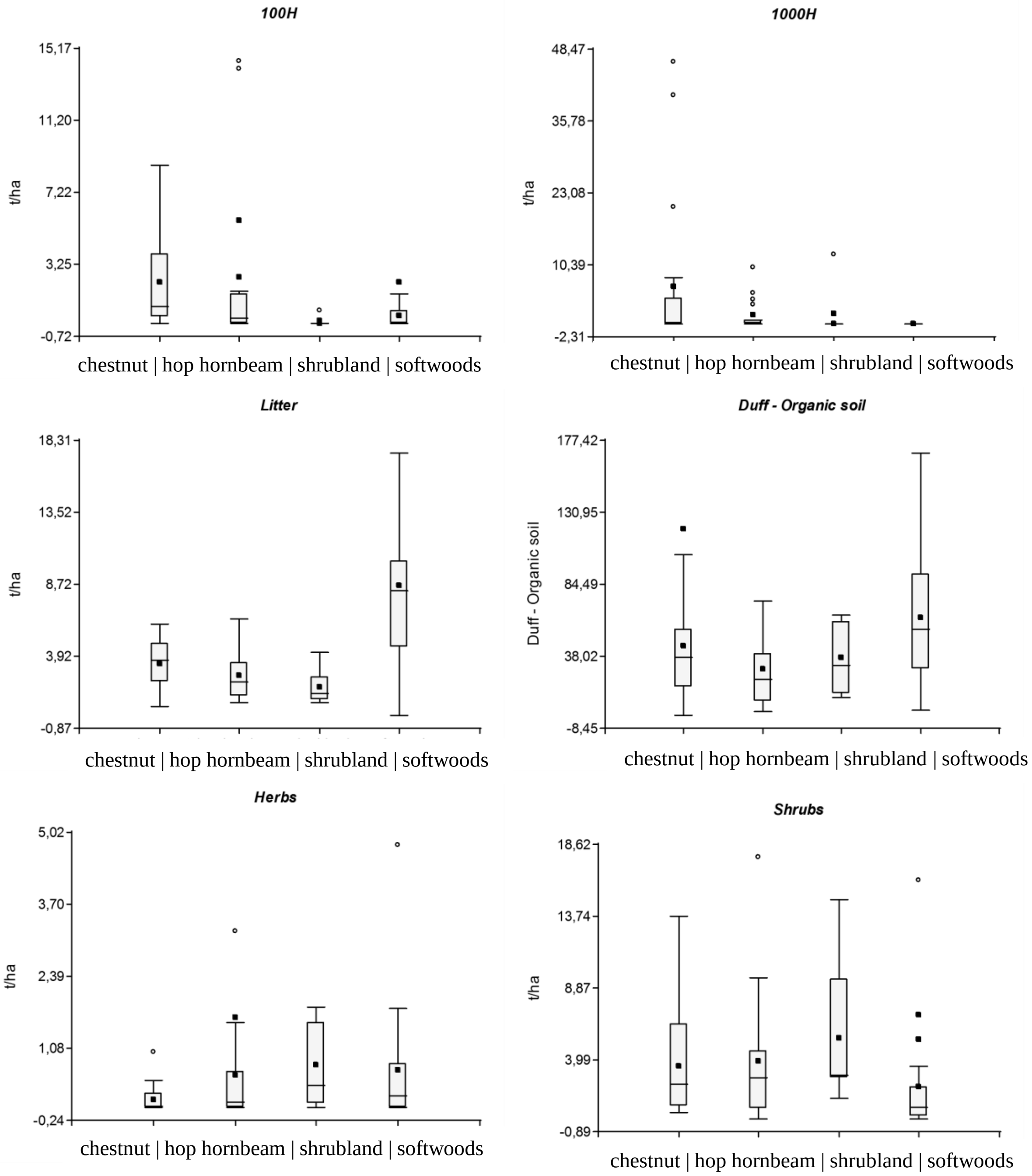


Figure 2.21– LL – Box and Whisker plots of measured loadings (t ha^{-1})

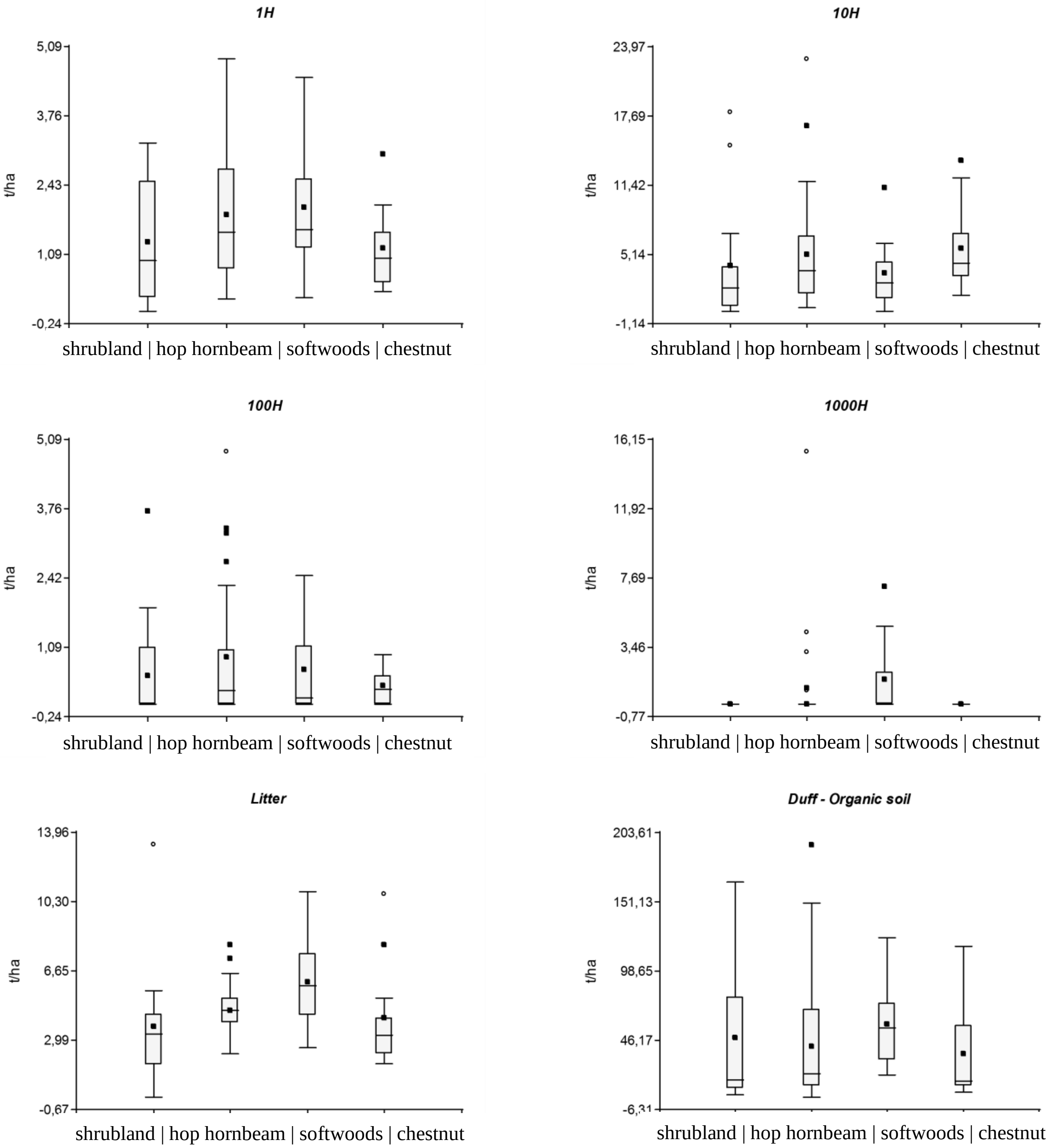


Figure 2.22– LL – Box and Whisker plots of measured loadings (t ha^{-1})

Table 2.8– LL – Sensitivity test (Kruskall-Wallis test p-value) to estimate the robustness of among-managements comparison of fuel loads (t ha^{-1}). Different letters mean pair comparison $p<0.05$

		management (n. of samples)			test	
fuel		**coppiced (21)**	**high forest (33)**	**unmanaged (7)**	**p**	
1h	medians	1.54^{B}	0.97^{A}	0.76^{A}	0.0163	*
10h	medians	6.34	0.97	0.76	0.0475	*
100h	medians	0.42^{B}	0.22^{AB}	0^{A}	0.0154	*
1000h	medians	0	0	0	0.0626	
Litter	medians	2.73^{A}	4.83^{B}	1.4^{A}	0.0027	**
Duff – O.S.	medians	30.03	48.52	32.34	0.4737	
Herbs	medians	0.03	0.18	0.41	0.2400	
Shrubs	medians	3.36B	0.88A	2.94B	0.0018	**
Fuelbed	medians	0.39B	0.18A	0.61B	0.0014	**

*P-Value <0.05 ** P-Value <0.01 ***P-Value<0.001

Table 2.9– MA – Sensitivity test (Kruskall-Wallis test p-value) to estimate the robustness of among-managements comparison of fuel loads (t ha^{-1}). Different letters mean pair comparison $p<0.05$.

		management (n. of sample)			test	
fuel		**coppiced (29)**	**high forest (16)**	**unmanaged (17)**	**h**	**p**
1h	medians	1.59	1.55	0.95	0.1800	
10h	medians	4.00	3.41	1.884	0.3008	
100h	medians	0.55^{B}	0.23^{AB}	0.00^{A}	0.0126	*
1000h	medians	0.00	0.00	0.00	0.0043	**
Litter	medians	3.92^{A}	5.22^{B}	4.17^{A}	0.0403	*
Duff – O.S.	medians	18.48	40	16.17	0.3048	
Herbs	medians	0.00^{A}	0.07^{A}	0.93^{B}	0.0029	**
Shrubs	medians	0.03	0.07	0.10	0.8060	
Fuelbed	medians	0.07	0.08	0.16	0.2135	

*P-Value <0.05 ** P-Value <0.01 ***P-Value<0.001

Table 2.10– LL – Sensitivity test (Kruskall-Wallis test P-value) to estimate the robustness of among-forest types comparison of fuel loads (t ha^{-1}). Different letters mean pair comparison p<0.05.

		Forest type (n. of samples)				Test	
fuel		**chestnut (12)**	**hop hornbeam (25)**	**shrubland (15)**	**softwoods (10)**	**p**	
1H	medians	1.21	1.64	0.76	0.90	0.0938	
10H	medians	7.02^{B}	6.07^{B}	1.98^{AB}	2.24^{A}	0.0101	*
100H	medians	0.88^{C}	0.29^{BC}	0.00^{A}	0.00^{AB}	0.0010	**
1000H	medians	0.00^{B}	0.00^{AB}	0.00^{AB}	0.00^{A}	0.0331	*
Litter	medians	3.65^{A}	2.24^{A}	1.4^{A}	8.27^{B}	<0.0001	***
Duff O.S.	medians	36.96	23.10	32.34	55.17	0.0651	
Herbs	medians	0.02	0.09	0.41	0.22	0.1577	
Shrubs	medians	2.33	2.8	2.94	0.75	0.0183	*
Fuelbed	medians	0.28^{AB}	0.39^{B}	0.61^{B}	0.14^{A}	0.0328	*

*P-Value <0.05 ** P-Value <0.01 ***P-Value<0.001

Table 2.11– MA – Sensitivity test (Kruskall-Wallis test P-value) to estimate the robustness of among-forest types comparison of fuel loads (t ha^{-1}). Different letters mean pair comparison p<0.05.

		Forest type (n. of samples)				Test	
fuel		**chestnut (12)**	**hop hornbeam (25)**	**shrubland (15)**	**softwoods (10)**	**p**	
1H	medians	1.02	1.52	0.97	1.57	0.2655	
10H	medians	4.36	3.72	2.08	2.61	0.217	
100H	medians	0.29	0.27	0	0.13	0.3157	
1000H	medians	0	0	0	0	0.0156	**
litter	medians	3.27^{AB}	4.53^{BC}	3.33^{A}	5.89^{C}	0.0158	**
Duff-O.S.	medians	15.02	20.79	16.17	55.17	0.1882	
herbs	medians	0.1	0	0.93	0.32	0.0769	
shrubs	medians	0.41	0	0	0.04	0.2182	
fuelbed	medians	0.16	0.07	0.14	0.1	0.7929	

*P-Value <0.05 ** P-Value <0.01 ***P-Value<0.001

Table 2.12– Fuel load comparison between the two study areas MA-LL (Mann Whitney test) separated for hardwoods and softwoods.

	Hardwoods			**Softwoods**		
Variable	LL	MA	p	LL	MA	p
1h (t ha^{-1})	1.55	1.56	0.9333	1.25	2.00	0.0310*
10h (t ha^{-1})	6.48	4.95	0.0249*	3.38	3.47	0.6625
100h (t ha^{-1})	2.00	0.67	0.0688	0.39	0.66	0.2686
1000h (t ha^{-1})	3.84	0.46	0.0031**	0,00	1.46	0.0036**
Herbs (t ha^{-1})	0.41	0.77	0.8109	0.66	0.56	0.9626
Litter (t ha^{-1})	2.85	4.23	0.0010**	8.65	6.04	0.1549
Duff - O.S.(t ha^{-1})	37.9	42.06	0.4488	63.07	58.41	0.9087
Shrubs (t ha^{-1})	3.99	0.76	<0.0001***	2.17	0.16	0.0064**
Fuelbed (m)	0.41	0.20	<0.0001***	0.24	0.11	0.0895

*P-Value <0.05 ** P-Value <0.01 ***P-Value<0.001

In LL, we found a significant influence of forest management on 1H, 10H, 100H ground dead wood, and a very significant influence on litter, shrubs and fuelbed (Table 2.8). The division in groups showed that high forests were more similar to unmanaged land than to coppice regarding ground dead wood (1H, 10H, 100H), instead for the other parameters (litter, shrubs, fuelbed) coppice and unmanaged land were similar to each other, high forests were instead very different (Table 2.8). In MA, forest management had a significant influence on 100H and litter, and a very significant influence on 1000H, litter and herbs. Coppices and high forests were more similar to each other than unmanaged land, apart from for litter (Table 2.9). The influence of management was not as clear as in LL.

In LL the different forest types showed significant differences for 10H, 1000H, shrubs and fuelbed, and a very significant difference for 100H and litter. Chestnut and hop hornbeam forests were always in the same groups, showing no significant differences. Shrubland was more similar to the broadleaved forests than to softwoods. Softwoods were well identified by a higher litter load than the other categories (Table 2.10).

In MA, the influence of forest type was much lower than in LL. Only 1000H and litter showed a significant difference (Table 2.11).

Given that we sampled in winter in MA, and in summer in LL, the differences between the two study areas were both geographic and seasonal. From the Wilkinson test (Table 2.12) it seems clear that differences between LL and MA were very slight in softwood plantations (fuelbed at 10%, 1H at 5%, shrubs and 1000H 1%). In softwoods, the differences in shrubs load and fuelbed height were mainly due to the decision to not consider saplings without leaves in winter in the fuel load. Broadleaves, instead, differ between study areas for most variables. In particular, significance was very high for fuelbed, shrubs and litter. These three variables were linked with the seasonal foliage fall. In winter the leaves fallen during autumn are still undecomposed and most shrubs don’t have leaves, so we didn’t count them for fuel load and fuelbed height.

Table 2.13– LL – Spearman correlation between fuel variables

fuel	**1H**	**10H**	**100H**	**1000H**	**Herbs**	**Litter**	**Duff-O.S.**	**Shrubs**
10H	0.28*							
100H	0.27*	0.35**						
1000H	0.21	0.36**	0.48***					
Herbs	-0.18	-0.12	-0.32*	-0.28*				
Litter	0.02	-0.1	0.02	-0.1	-0.15			
Duff-O.S.	-0.28*	-0.18	-0.15	-0.23	0.06	0.042**		
Shrubs	0.06	0.28*	0.16	0.29*	-0.1	-0.26*	-0.19	
Fuelbed	0.07	0.08	-0.13	0.07	0.08	-0.32*	-0.16	0.56***

*P-Value <0.05, ** P-Value <0.01, ***P-Value<0.001

Table 2.14– MA – Spearman correlation between fuel variables

fuel	**1H**	**10H**	**100H**	**1000H**	**herbs**	**litter**	**Duff-O.S.**	**shrubs**
10H	0.55***							
100H	0.36**	0.43**						
1000H	0.24	0.21	0.32**					
Herbs	-0.29*	-0.25*	-0.33**	-0.1				
Litter	0.32**	0.07	0.17	0.19	-0.3			
Duff-O.S.	0.18	0.06	-0.07	0.03	0.31*	0.27*		
Shrubs	0.39**	0.36**	0.16	-0.03	0.21	-0.02	0.14	
Fuelbed	0.05	0.06	-0.25*	-0.16	0.55***	-0.12	0.39**	0.51***

*P-Value <0.05 ** P-Value <0.01 ***P-Value<0.001

Table 2.15– LL – Spearman correlation between fuel load and environmental variables

variable / fuel	**1H**	**10H**	**100H**	**1000H**	**herbs**	**litter**	**Duff-O.S.**	**shrubs**	**fuelbed**
trees diameter	-0.15	-0.19	0.05	-0.14	-0.06	0.57***	0.26*	-0.52***	-0.43***
trees height	-0.19	-0.11	0.17	0.0014	-0.07	0.2	0.17	-0.39**	-0.37**
slope	0.17	0.31**	0.40**	0.39**	-0.21	-0.31**	-0.28*	0.27*	0.17
dead trees	0.16	0.37**	0.46***	0.36**	-0.03	-0.01	-0.16	0.38**	0.37**
canopy closure	0.31**	0.2	0.14	0.24	-0.45***	0.05	-0.03	-0.06	-0.11
shrubs cover	0.23	0.12	-0.06	0.17	0.08	-0.30*	-0.28*	0.58***	0.66***
herbs cover	-0.39**	-0.23	-0.33**	-0.29*	0.73***	-0.24	0.06	-0.12	0.18
basal area	0.14	0.23	0.45***	0.2	-0.38	0.30*	0.24	0.15	-0.16

*P-Value <0.05 ** P-Value <0.01 ***P-Value<0.001

Table 2.16– MA – Spearman correlation between fuel load and environmental variables

variable / fuel	**1H**	**10H**	**100H**	**1000H**	**herbs**	**litter**	**Duff-O.S.**	**shrubs**	**fuelbed**
trees diameter	0.19	0.14	0.23	0.32**	-0.49***	0.35**	-0.17	0.03	-0.28*
trees height	0.27*	0.25	0.25	0.36**	-0.41**	0.2	-0.03	0.13	-0.23
slope	0.16	0.18	0.09	0.07	0.4**	0.09	0.42**	0.03	0.29*
dead trees	0.13	0.29*	0.18	-0.17	-0.14	0.04	0.26	0.26*	0.31*
canopy closure	0.38**	0.41	0.36**	0.17	-0.47**	0.36**	0.08	0.13	-0.21
shrubs cover	0.15	0.29*	0.1	-0.06	0.03	0.01	-0.14	0.54***	0.36**
herbs cover	-0.2	-0.21	-0.42**	-0.09	0.75***	-0.16	0.32**	0.1	0.49***
basal area	0.33**	0.31*	0.37**	0.26*	-0.44**	0.17	0.19	-0.02	-0.18

*P-Value <0.05 ** P-Value <0.01 ***P-Value<0.001

Table 2.17– Cumulated Probability Density characteristic curves

	LL			MA		
Variable	**Samples**	**Formula**	**r2**	**Samples**	**Formula**	**r2**
1h	61	y = 1.1757e-0.823x	0.98	61	$y = 1,3226e^{-0,779x}$	0.96
10h	57	y = 1.2954e-0.215x	0.95	58	$y = 0,9991e^{-0,204x}$	0.98
100h	36	y = -0.235ln(x) + 0.5169	0.97	36	y = -0,239ln(x) + 0,3851	0.95
1000h	13	y = -0.151ln(x) + 0.9544	0.91	8	y = -0,289ln(x) + 0,7576	0.94
Herbs	45	y = -0.175ln(x) + 0.2349	0.98	37	y = -0,201ln(x) + 0,3531	0.98
Litter	60	y = 1.1057e-0.236x	0.98	61	$y = 2,592e^{-0,431x}$	0.97
Duff-O.S.	60	y = 1.3142e-0.028x	0.97	62	y = -0,271ln(x) + 1,3808	0.99
Shrubs	58	y = 0.8438e-0.238x	0.98	38	$y = 0,674e^{-0,555x}$	0.89
Fuelbed	61	y = 1.2487e-3.429x	0.95	62	$y = 0,7868e^{-4,296x}$	0.94

1H, 10H, 100H dead woods were positively correlated with each other in both LL and MA. Instead, 1000H dead wood was positively correlated with 100H but not with 1H in both study areas. In LL, 1000H was also well correlated with 10H ($p=0.004$). Herbs were generally negatively correlated with ground dead wood in both study areas. Litter did not show clear correlations: it was correlated with duff-organic soil in LL ($p<0.001$) and with 1H in MA ($p=0.01$), but negatively correlated with shrubs in LL ($p=0.04$).

Duff-organic soil showed opposite correlations in the two study areas, it was negatively correlated with 1H ($p=0.03$) and 100H ($p= 0.04$) in LL but not in MA, and strongly correlated with litter in LL ($p<0.001$) and correlated with herbs in MA ($p=0.02$). Shrubs showed correlations with fine dead wood (1H, 10H) but not with coarse dead wood. Fuelbed was strongly correlated with shrubs in both areas and with herbs in MA ($p<0.001$). It showed a negative correlation with litter in LL ($p=0.01$) and a positive correlation with duff-organic soil in MA ($p=0.001$) (Table 2.13- 2.14).

1H was well correlated with canopy closure in both areas, and with tree height and basal area in MA. It was also negatively correlated with herbs cover in LL ($p=0.001$). Dead wood (10H, 100H, 1000H) were well or highly correlated with slope and dead trees in LL, instead this correlation was limited for 10H and dead trees in MA ($p=0.05$). 10H, 100H, 1000H had a negative correlation with herbs cover, in particular in LL. All dead wood classes were correlated with basal area in MA, instead in LL only 100H was well correlated (p=0.001). Herbs were well negatively correlated with canopy closure in both areas and also with tree height and basal area in MA. Litter was strong correlated with trees diameter (p<0.001) and negative correlated with slope (p=0.01) and shrubs cover (p=0.02) in LL. Instead, in MA litter was well correlated with trees diameter and canopy closure (p=0.004). Duff-organic soil correlations were very different between LL and MA; in LL it was positively correlated with trees diameter (p=0.04) and negative correlated with slope and shrubs cover, while in MA it was positively correlated with slope and herbs cover (p=0.01).

Shrubs were correlated with dead trees in both areas. In LL they were also correlated with slope and strongly negatively correlated with trees diameter (p<0.001) and tree height (p=0.002) (Table 2.15 -2.16).

Fuels never had a normal distribution of CDF. The most common distribution was exponential (1H, 10H, litter, shrubs, fuelbed, and duff-organic soil in LL), apart from 100H, 1000H, herbs and duff-organic soil in MA that had a logarithmic distribution. The fuels with logarithmic distribution were the ones with the fewest samples. All the curves were highly significant with an R^2 higher than 0.90. LL and MA had the same kind of distributions and similar values of R^2 (Table 2.17). Only duff – organic soil had a different distribution between LL and MA.

Fuel models

We aggregated fuel data using three classification systems: association based on forest types; direct classification based on forest structure; direct classification with cluster analysis (Keane 2013). The custom models parameters are summarized in Table 2.19.

In detail:

<u>Forest types</u> - We developed four fuel models for each study area: chestnut, hornbeam, shrubland and softwood plantations (Table 2.19), plus a grass model in MA. Similarly to what is reported in data analysis, in LL area, the chestnut model (LCH) and hop hornbeam model (LHO) were similar in fuel load. They had a high quantity of 1H, 10H and shrubs (Table 19). Fuelbed was not very high (20 cm), so the fuels were quite compact. Shrubland (LNA) had a lower amount of fine dead fuels

than LCH and LHO and a very low coarse dead wood load. In shrubland, broadleaved shrubs were the main fuel (2.94 t ha^{-1}). Softwood plantations (LSP) had a very high amount of fine fuels (9.17 t ha^{-1}) due mainly to the thick layer of undecomposed litter. In LSP, shrubs and herbs had a low influence. The fuelbed was quite low (10 cm) and the fuel was very compact (Table 2.19).

In the MA area, chestnut (MCH) and hop hornbeam (MHO) had similar fuel loads with a high amount of 1H and 10H and a very low amount of herbs and shrubs (Table 2.19). Unlike in the LL, litter was the main component of 1H fuels. The fuelbed was low for chestnut (16 cm) and very low for hop hornbeam (7 cm). The shrubland (MNA) had a lower amount of 1H and 10H than forests, but an influent amount of herbs (0.93 t ha^{-1}) (Table 19). No shrubs load was reported in MNA because all the shrubs were without leaves in the winter. For the same reason the shrubland fuelbed was low (15 cm). Softwood plantations (MSP) had a high amount of 1H (7.46 t ha^{-1}) compared with broadleaves but anyway lower than softwood plantations in LL. Herbs and shrubs load was low and the fuelbed was very low (10 cm), so the fuel was quite compact. Grassland (MGR) had mainly 1H (2.14 t ha^{-1}) and herbs load (2.77 t ha^{-1}). The fuelbed was not very high (18 cm) (Table 2.19).

Prometheus - Not all Prometheus classes were covered by the data collected. The aggregation resulted in four fuel types for LL (classes 3,5,6,7) and four for MA (classes 2,5,6,7). In the MA area just one sample was in class 3 but since it was not representative, we did not use that class.

In LL, fuel model LP3 had mainly fine dead wood 1H (2.35 t ha^{-1}) and 10H (3.53) and a high amount of live fuel: herbs (1.6 t ha^{-1}) and live woody (3.6 t ha^{-1}) (Table 19), so it strongly depended on the live fuel moisture condition. The fuelbed height was 54 cm. In fuel model LP5 the main fuel was the litter (1H, 7,05 t ha^{-1})) but it also had a significant amount of 10H (2.98 t ha^{-1}). Herbs and live woody had a low load and did not influence the fuelbed height that was very low (7 cm). Fuel model LP6 had fuel load values intermediate between LP5, main fuels were 1H (4,61 t ha^{-1}) and 10H (4.70 t ha^{-1}). Fuelbed was 32 cm. Fuel model LP7 had a very high total fuel load16.14 t ha^{-1}, due both to fine fuels 1H (4.28 t ha^{-1}), 10H (6.67 t ha^{-1}) and to live woody (4.99 t ha^{-1}). Fuelbed height was 78 cm.

In MA area abandoned pasture was richer in grass and poorer in shrubs compared with LL, so instead of model 3 we had model 2. The main fuels of model MP2 were 1H (2.85 t ha^{-1}) and herbs

(2.46 t ha^{-1}). The fuelbed was quite low (16 cm). The model MP5 was similar to the LL one: it was rich in 1H (5.95 t ha^{-1}) and 10H (3.96 t ha^{-1}) and it had a very low fuelbed (3 cm), so was very compact. The model MP6 was similar to that in the LL but had a lower shrubs load (0.81 t ha^{-1}). The model MP7 was rich in fine dead wood and shrubs but with a lower total live woody load (2.03 t ha^{-1}) than in LL (Table 2.19).

Cluster - Cluster analysis resulted in four fuel models for LL and four for MA (Table 2.17). In LL, the cluster LC1 included mainly dense softwood plantations with a very thick litter layer. 1H was the main fuel (10.84 t ha^{-1}). Herbs and shrubs load was very low and fuelbed height was 11 cm. Cluster LC2 included forests with light litter and fine dead wood fuel. The main fuels were 1H (4.34 t ha^{-1}) and 10H (5.96 t ha^{-1}), in addition there were some scattered shrubs. Fuelbed was 19 cm. It was typical of broadleaved high forests but also included some coppices and hardwood high forests. Cluster LC3 was typical of broadleaved forests with phytosanitary problems. It was rich in ground dead wood (1H (5.79 t ha^{-1}, 10H 8.42 t ha^{-1}), 100H 8.68 t ha^{-1}), and tall shrubs (3.37 t ha^{-1}). Cluster LC4 had little litter and fine dead wood (1H 3.8 t ha^{-1}, 10H 5.59 t ha^{-1}) and was very rich in live woody (5.87 t ha^{-1}). It was typical of abandoned farmland, young coppices and low density high forests (Table 2.18-2.19).

In MA study area, the cluster MC1 included plots with light litter and fine ground dead wood (1H 5.51 t ha^{-1}) and no undergrowth. It included almost half of the plots and was found in every kind of forest type and forest management. It was typical of dense forest. Cluster MC2 had a high total fuel load (15.79 t ha^{-1}), the main fuels were 1H (8.9 t ha^{-1}), 10H (4.65 t ha^{-1}) and shrubs 1.52 t ha^{-1}). The fuelbed was not very high (31 cm). It was found in all the forest types, but was typical mainly of young coppices and unmanaged forest. Cluster MC3 was typical of abandoned pastures, the main fuels were herbs (3.32 t ha^{-1}), litter and fine dead wood (1H 2.36 t ha^{-1}). Cluster MC4 had high amount of ground dead wood, both fine and coarse (1H 5.77 t ha^{-1}, 10H 5.37 t ha^{-1}, 100H 3.02 t ha^{-1}). It could be typical of hardwood coppices or unmanaged softwood high forests (Table 2.18-2.19).

Table 2.18 - Forest fire management and forest type in cluster classification.

LL				MA			
Cluster	**Management**	**Main forest type**	**Number of plots**	**Cluster**	**Management**	**Main forest type**	**Number of plots**
1	coppiced	hop hornbeam	1	1	coppiced	chestnut	3
1	high forest	chestnut	1	1	coppiced	hop hornbeam	10
1	high forest	softwoods	9	1	coppiced	shrubland	3
2	coppiced	chestnut	4	1	high forest	chestnut	3
2	coppiced	hop hornbeam	3	1	high forest	hop hornbeam	2
2	high forest	chestnut	6	1	high forest	softwoods	6
2	high forest	hop hornbeam	3	1	unmanaged	chestnut	2
2	high forest	softwoods	6	1	unmanaged	shrubland	1
2	unmanaged	shrubland	1	2	coppiced	chestnut	2
3	coppiced	chestnut	1	2	coppiced	hop hornbeam	4
3	coppiced	hop hornbeam	3	2	coppiced	shrubland	1
3	high forest	chestnut	1	2	high forest		3
4	coppiced	chestnut	4	2	unmanaged	chestnut	2
4	coppiced	hop hornbeam	5	2	unmanaged	hop hornbeam	3
4	high forest	chestnut	2	2	unmanaged	shrubland	1
4	high forest	hop hornbeam	1	3	unmanaged	hop hornbeam	1
4	high forest		4	3	unmanaged	shrubland	7
4	unmanaged	shrubland	6	4	coppiced	hop hornbeam	4
				4	coppiced	shrubland	2
				4	high forest	hop hornbeam	1
				4	high forest	softwoods	1

Table 2.19 - Custom fuel models attributes

area	description	fuel model code	1H t ha^{-1}	10H t ha^{-1}	100H t ha^{-1}	live herb t ha^{-1}	live woody t ha^{-1}	1H s area/vol ratio 1/cm	herbs area/vol ratio 1/cm	live woody area/vol ratio 1/cm	Fuel Bed Depth m	Dead fuel ext. moisture %
Forest types												
L	chestnut	LCH	4.86	7.02	0.88	0.02	2.33	66	59	52	0.20	25
L	hop hornbeam	LHO	3.88	6.07	0.29	0.09	2.80	66	59	52	0.27	25
L	shrubland	LNA	2.16	1.98	0.00	0.41	2.94	52	59	46	0.43	20
L	softwoods plantation	LSP	9.17	2.24	0.00	0.22	0.75	66	59	52	0.10	25
M	chestnut	MCH	4.29	4.36	0.29	0.10	0.50	66	59	52	0.16	25
M	hop hornbeam	MHO	6.05	3.72	0.27	0.00	0.31	66	59	52	0.07	25
M	shrubland	MNA	4.30	2.08	0.00	0.93	0.00	52	59	46	0.15	20
M	softwoods plantation	MSP	7.46	2.61	0.13	0.32	0.42	66	59	52	0.10	25
M	grassland	MGR	2.14	0.62	0.00	2.77	0.00	66	59	52	0.18	15
Prometheus												
L	shrubs	LP3	2.35	3.53	0.00	1.50	3.6	52	59	46	0.54	15
L	timber litter	LP5	7.05	2.98	0.70	0.13	0.74	66	59	52	0.07	25
L	low timber understory	LP6	4.61	4.70	0.34	0.07	1.70	66	59	52	0.32	20
L	middle timber understory	LP7	4.28	6.72	0.10	0.05	4.99	49	59	25	0.78	20
M	grassland and shrubs	MP2	2.85	0.83	0.00	2.46	0.00	66	59	52	0.16	15
M	shrubs	MP3	5.73	16.83	1.05	1.32	7.26	52	59	46	0.22	15
M	timber litter	MP5	5.95	3.96	0.60	0.00	0.21	66	59	52	0.03	25
M	low timber understory	MP6	7.04	3.85	0.13	0.30	0.81	66	59	52	0.29	20
M	middle timber understory	MP7	6.41	4.52	0.17	0.16	2.03	49	59	25	0.90	20
Cluster												
L	deep litter, sparse shrubs	LC1	10.84	1.90	0.21	0.12	0.74	66	59	52	0.11	25
L	light litter, sparse shrubs	LC2	4.34	5.96	0.42	0.13	0.89	52	59	46	0.19	20
L	coarse GDW, tall shrubs	LC3	5.79	8.42	8.68	0.00	3.37	52	59	46	0.67	20
L	light litter, shrubs	LC4	3.80	5.59	0.00	0.17	5.87	72	66	52	0.50	20
M	light litter	MC1	5.51	2.38	0.01	0.00	0.00	66	59	52	0.06	25
M	deep litter, shrubs	MC2	8.90	4.65	0.57	0.15	1.52	52	59	46	0.31	20
M	scattered trees, grass	MC3	2.36	0.37	0.00	3.32	0.00	52	59	46	0.20	20
M	litter and coarse GDW	MC4	5.77	5.37	3.02	0.00	0.02	72	66	52	0.05	20

Discussion

Fuel characteristics and fuel load

In the Colli Euganei, chestnut and hornbeam forests were similar in forest structure and fuel load (Table 2.6) They could be considered as a unique class (Table 2.10). Compared to what was reported by Fernandes et al. (2009) for *Acacia* spp. and deciduous oaks in Portugal, chestnut and hop hornbeam forests had a similar amount of 1H and shrubs but had much more coarse dead wood 10H, 100H. Marchetti (Veneto 1999) reported a higher amount of 1H (6.21 t ha^{-1}) in chestnut forest and a much lower amount of 10H, 100H and shrubs. In hop hornbeam forest Marchetti measured a very high amount of 1H (8.22 t ha^{-1}) and an average amount of 10H (3.76 t ha^{-1})(Veneto 1999). Alpi orobiche broadleaved forests had 6.99 t ha^{-1} 1H and 3.93 t ha^{-1} 10H and Serre costiere Calabre broadleaved forests 3.68 t ha^{-1} of 1H and 2.17 t ha^{-1} of 10H (Marchetti and Lozupone 1995). In all cases, the amount of 1H that we measured was comparable between LL study area and the literature, but the amount of 10H, 100H and shrubs were much higher in the study area than in the literature. This difference could be due to the phytosanitary problems that affect the Colli Euganei forests, particularly in the case of chestnut. Chestnut forests in Colli Euganei were suffering from ring shake defect, chestnut blight disease (Bounous 2002) and *Dryocosmus kuriphilus* outbreaks (Graziosi and Santi 2008). In hop hornbeam forest, several species had defoliation caused by *Barbites vicetinus* (Galvagni and Fontana, 1993), a local locust outbreak in the last years. In addition, some forests had many dead trees because of drought and fires in 2003.

We found differences between MA and LL forests: chestnut and hornbeam in the Colli Euganei were generally in worse phytosanitary condition than in MA, so the amount of high foresting dead trees, coarse dead wood (100H, 1000H) and shrubs is higher (Table 2.6 –2.7). Litter load is higher in MA, probably because we sampled in winter when the foliage that fell during the autumn was still undecomposed (Table 2.12). Forest management influences the fuel load and forest structures (Table 2.8 – 2.9). Coppices usually have more shrubs and grass, and less litter than high forests. This could suggest a higher fire risk in coppices when the live fuels have a low moisture content (Table 2.8 – 2.9).

In MA, softwood plantations have 1H and 10H values a bit higher than that reported in Fernandes (2009) for *Pinus pinaster* and a similar range for 100H and live fuels. 1H in the study area is lower than in Dimitrakopoulus (2002) (11.68 t ha^{-1}). Marchetti (Veneto 1999) reported a similar value for 1H (9.4 t ha^{-1} in *Pinus sylvestris* and 10.69 t ha^{-1} in *Pinus nigra* but lower values for 10H (1.28 t ha^{-1} and 1.21 t ha^{-1} respectively) (Table 2.6). Overall, softwood plantations in the study area are similar to what is reported in the literature apart from the high amount of 10H.

LL shrublands have a high amount of live fuels and a not very high amount of 1H, so shrubs are the fuel that determines fire behaviour (Table 2.6).

MA shrublands have very variable tree and shrub cover because the class includes full density shrublands, where there is just litter on the ground, and abandoned pastures with tall grass and scattered trees. The average value obtained from the data shows an average situation that could represent a pasture abandoned for a long time but that has not yet reached full shrubs density. In MA shrublands, fuel load (Table 2.7) is very similar to what Marchetti and Lozupone (1995) reported for grassland and shrubs.

Further study would be useful to better describe abandoned pastures, since they were the most commonly burned vegetation. In the plots with a dominance of grass cover, live grass load is similar to the one found in pastures still in use before the grazing (Boschetti *et al.* 2007, Franca *et al.* 2012), and they also have a litter layer due to ungrazed dead grass and shrubs foliage that almost double the fuel load (Table 2.7). Franca (2007) reported a significant increment of fire risk in ungrazed pastures.

The very few significant differences between chestnut and hop hornbeam forests could suggest that in deciduous broadleaves the dominant species is not the main source of fuel variability.

Softwood plantations show litter differences between MA and LL (Table 2.13), also if they included different species. This could be because most of these plantations do not have an economic value, so were unmanaged and usually too dense. Where, due to tree deaths or thinning, the density is not full, a thick undergrowth of *Rubus* spp. and local hardwood immediately grows. In this kind of forest a description based only on forest type always fails to describe the real situation.

Correlations between fuels show few clear results (Table 2.13 – 2.14): fine and medium fuels 1H, 10H, 100H always show a positive correlation with each other, instead 1000H shows a correlation with 100H and in LL with 10H but never with 1H, so coarse dead wood deposition probably follows different dynamics than fine dead wood. Herbs are generally negative correlated with ground dead wood since herb load is higher in low density forests, where there is less woody material deposition. Litter and duff-organic soil have very different correlations between the two study areas. Probably the influence of local factors could have a major effect. Good correlation between litter and fine dead wood litterfall is found in Keane (2008).

The correlations between fuels and environmental factors (Table 2.14–2.15) have some differences between LL and MA. The dead wood load in MA is greater in height and dense forests, as recorded for fine fuels in Keane (2008). Instead the amount of dead wood in LL is poorly correlated with forest density but is mainly determined by forest health (dead trees). So the phytosanitary conditions probably have a greater influence on litterfall than forest structure. Litter is shown to be higher in tall and dense forests. Shrubs load correlations were also stronger in LL than in MA; shrubs load is very low in healthy, tall and full density forests. Phytosanitary problems could increase the amount of sunlight reaching the undergrowth, in this way improving shrubs load.

In the study areas, the fuels cumulated density function never had a normal distribution. In most cases, the distribution is exponential (Table 2.16) and in a few it is logarithmic. Logarithmic or exponential distribution of fuel are reported in the literature (Parresol *et al.* 2012). It is interesting that the two study areas have very similar distributions. Exponential distribution is common for tree age in uneven forest (Wagner 1978) or tree diameter (Bailey and Dell 1973), leaves load on the trees is exponentially correlated with tree diameter (Rapp and Bachelier 1971). The high forest forest fire survivorship has a negative exponential curve (Yarie 1981). These similarities in distributions suggested a link between forest structure and fuel load.

Fuel models

The association method based on forest type is easy to implement but has some caveats. Fuel characteristics are rarely correlated with vegetation attributes and categories, especially at fine scale (Keane *et al.* 2012). One reason for this lack of relationship between fuels and vegetation is that vegetation attributes, such as species cover and height, vary at coarser scale than wildland fuels (Keane *et al.* 2012). In fact, chestnut and hop hornbeam forest models are not well differentiated from each other (Table 2.19) and could be summarised in just one model. Sampling plots in softwood plantations were found to have two different structures: high density forest with litter and dead wood on the ground, or not full density forests with a dense shrub undergrowth. The association method creates a medium way model that does not really represent the two situations. Shrublands also have a very high variety of structure that cannot be represented correctly by just one model.

Direct classifications contain categories that can be uniquely identified and can be used in fire applications such as simulating fire (Keane 2013). Since direct fuel classifications have low redundancy between class attributes, they can be used for populating fire models and identifying thresholds of fire behaviour and effects (Lutes *et al.* 2009). The direct classifications are empirically driven and require extensive datasets to represent the diversity of fuelbed in the analysis (Keane 2013). In fact, classifying the collected data in Prometheus classification (Giakoumakis *et al.* 2002, Riano *et al.* 2003), we were not able to cover all the Prometheus classes, and some classes were represented by few samples (classes 2, 3 and 7). Cluster fuel models were well differentiated from each other and easy to recognize in the forest. Cluster classification based on fuel load created fuel models having in some cases very high or very low fuel load that represent some particular situations and that can hardly be applied to extensive maps.

Conclusions

Fuel load in the study areas is similar to what is found in the literature in similar kinds of forests, apart from the amount of ground dead wood and shrubs in LL that was particularly high, probably because of several phytosanitary problems affecting Colli Euganei forests. Further investigation would be useful for underhigh foresting the connection between fuel load and forest health.

The very few significant differences between chestnut and hop hornbeam forests suggest that species are not the main cause of variability in fuel load. An investigation in other forest types would be needed to confirm this.

Softwood plantations is a large category that includes many different species, and in most plots they are unmanaged full density plantations. Despite this, the only very significant difference between MA and LL was in the shrubs load. In this category we can find two different situations: full density unmanaged plantation, in this case shrub and herb fuels are almost absent, and not full density plantations because of thinning, in this case the soil was covered by a deep layer of shrubs (mainly *Rubus* ssp*.).* In this situation, a classification based only on species was not able to represent the fuel variability.

Forest management has a significant influence on forest fuels. In full density high forests the main fuels are litter and fine dead wood, instead in coppices, shrubs and grass load can become the main fuels. Abandoned farmland and pastures are usually rich in herbs and shrubs, and can have a high variability in structure and fuel load.

Fuel distributions have exponential or logarithmic curves, as found in other forest parameters. Some correlations between fuel loads and between forest structure and fuel load have been found, in some cases correlations are strong and similar in the two study areas, in others there are contradictory results between study areas.

The fuel classification method base on forest type is easy to create and is directly associable to forest maps, but it represents an average situation and is not able to catch fuel variability. Using this method custom fuel models can be quite similar to each other. Direct classification by forest structure creates fuel models well differentiated and easy to identify in the forests, but the low number of samples don’t allow all kinds of forest structures to be covered and it is not correlated with forest type, so is not directly associable to a forest map. Lastly, direct classification obtained by clustering fuel load shows very well-defined fuel models but that in some cases are associated with end-scale fuel conditions and so become difficult to use on a large scale.

Differences between fuel models need to be measured simulating real fires using a fire propagation model.

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Chapter III

Testing different custom and standard fuel models using FARSITE in the Eastern Italian Alps

Introduction

Fire modelling and information system technology can play a critical supporting role in fire management activities, including assessment of the current situation, projecting into the future, and especially the evaluation of alternatives (Andrews and Queen 2001). 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 and Queen 2001). Such models are therefore vital for planning fire suppression and fuel management (Keane *et al*. 2002).

As pointed out by several previous works, wildfire spread is a complex spatial and temporal dynamic process that depends on many factors such as weather, topography, fuel types and fuel moisture content (Carvalho *et al*. 2006, Santoni *et al*. 2011, Salis *et al*. 2014, Salis *et al*. 2015, Jahdi *et al*. 2015). Several surface spread models have been developed under many conditions in different areas around the world, particularly where wildfires are threatening forests, valued resources and human lives (Pastor *et al*. 2003, Perry 1998, Sullivan 2009). These models are implemented to simulate complex physical-chemical and dynamic processes over large and spatially heterogeneous landscapes and under changing weather and fuel moisture conditions (Arca *et al*. 2009, Finney 1998, Arca *et al*. 2007b, Forthofer 2007, Ager *et al*. 2010, Salis *et al*. 2015).

FARSITE is a spatial and temporally explicit fire simulation system developed at the Missoula Fire Sciences Laboratory of the USDA Forest Service and is still currently one of the most used and user-friendly simulators. The simulator, which is a semi-empirical model based on Rothermel's (1972) surface fire spread model, simulates fire growth using Huygens's principle wave propagation and fire intensity using Byrams (1959) equation. FARSITE has been widely calibrated in the US and employed not only to generate spatial maps of fire spread and behaviour (Finney and Ryan 1995, Finney 1998) but also to evaluate the effects of different forestry prescriptions and fuel treatment options on reducing fire hazard (Cochrane *et al*. 2012, Finney 2001, Schmidt *et al*. 2008, Stephens 1998, Stratton 2004). The use of FARSITE simulator on different areas from those where the model was originally developed requires a local calibration and validation (Arca *et al*. 2007a) using observed wildfire data and is the primary step to applying the simulator at larger scales (Ager *et al*. 2007, Salis *et al*. 2013, Stratton 2006).

FARSITE requires a set of geospatial input data concerning topography, surface fuel models, canopy characteristics and the physical parameters of the fuel bed, fuel moisture content and weather data. The fire modelling outputs in turn strongly depend on the resolution and reliability of the input data, especially as far as weather data and fuel models are concerned (Arca *et al*. 2007a).

A generalized description of fuel properties based upon average fuel conditions, called a fuel model, is typically used to describe the physical characteristics of a fuel type in an area.

Fire behaviour fuel models describe the fine fuel that carries fire spread, as required by Rothermel's model (Bacciu *et al*. 2009). 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).

Commonly used fire behaviour fuel models were initially developed in the US by Anderson (1982) and more recently by Scott and Burgan (2005). The use of these models outside their original area requires local validation to ensure they are representative of local fuel conditions.

Fuel assessment requires a linkage system to associate the floristic traits of certain cover types with fire behaviour determinants (Koutsias 2003). There are three broad approaches for fuel description based on the processes used to develop the description: 1) association; 2) classification (direct or indirect); 3) abstraction (Keane 2013). In the association method, fuel information is assigned to categories in extant classifications. In direct classification the fuel data are clustered into similar groups using statistical techniques. In indirect classification, individual fuelbeds are identified and sampled in the field and fuelbed is added as another category in the classification. Lastly, in the abstraction method fuel inputs to fire models are adjusted to match observed fire behaviour, and the adjusted fuel information becomes a category in the classification (Keane 2013).

In Europe, the most studied forest types for fire behaviour fuel models have been Mediterranean scrubland (Bacciu *et al*. 2009, Baeza *et al*. 2006, Pereira *et al*. 1995) and pine forests (Camia 1994, Fernandes 2009, Arpaci *et al*. 2011). Fuel conditions have seldom been studied in the common deciduous broadleaf forest types (Marchetti and Lozupone 1995, Giakoumakis *et al*. 2002).

In the Alps the application of fire behaviour fuel models in spatial and temporally explicit fire simulation systems is still uncommon. FARSITE had some local applications (Ascoli *et al*. 2007, Ascoli *et al*. 2015, Variara 2014), but no large-scale applications have so far been recorded.

This chapter evaluates the application of FARSITE in an Alpine area, to analyze how much the different fuel classification methods affected fire simulation accuracy and select a set of surface fuel models to use in further fire behaviour applications in the Alps.

Materials and methods

Study area

According to the regional fire regime analyzed in chapter one, we separated the region in two study areas: the mountain area (MA) where forest fire risk is higher in winter, from January to March; the fires can be quite big and their behaviour is strongly dependent on orography. The lowlands (LL) where forest fire risk is higher in summer, from June to August; fires are usually small, but because of the high population density, they have a high wild urban interface risk. Study areas are shown in Figure 3.1.

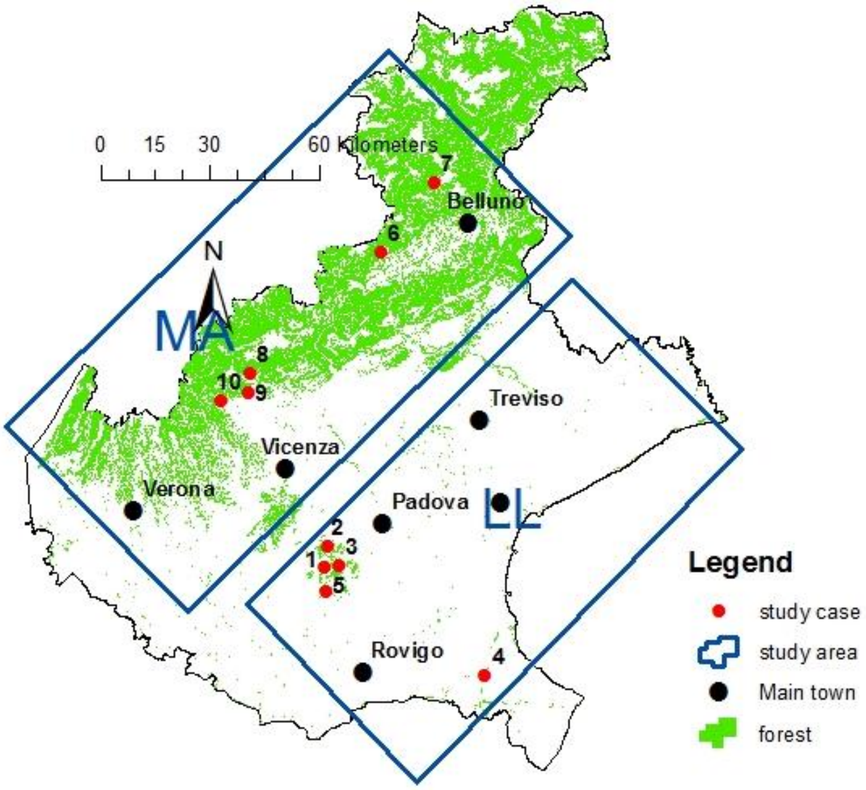


Figure 3.1 - Study area and case study distribution

Case study

We simulated 10 fires that happened in Veneto Region between 2003 and 2012. Five of them are in LL and five in MA. Fires are listed in Figure 3.1 and Table 3.1.

Table 3.1 - Case study

code	**Name**	**Ignition**	**Suppression**	**Burned area (ha)**	**Main fuel types (chapter 2)**	**Area**
1	Vendevolo	13/07/2003 21:15	15/07/2003 23:15	10.0	chestnut	LL
2	Grande	15/08/2003 21:00	16/08/2003 17:00	30.7	chestnut	LL
3	Rua	21/09/2003 15:25	23/09/2003 10:00	48.0	chestnut, hop hornbeam, softwoods	LL
4	San Giusto	10/05/2012 16:00	10/05/2012 20:40	2.3	softwoods	LL
5	Cero	03/08/2012 14:15	03/08/2012 20:45	2.2	hop hornbeam	LL
6	San Mauro	06/02/2011 13:00	09/02/2011 15:13	312.0	grassland, shrubland, hop hornbeam	MA
7	La Muda	10/05/2011 13:43	14/05/2011 12:30	269.0	softwoods, hop hornbeam, shrubland, grassland	MA
8	Costo	25/01/2012 10:30	26/01/2012 06:00	96.5	grassland, shrubland, hop hornbeam, softwoods	MA
9	Grumello	26/01/2012 14:00	27/01/2012 07:29	4.2	hop hornbeam	MA
10	Paladini	30/03/2012 11:00	31/03/2012 18:27	7.7	chestnut, beech	MA

For all case studies, ignition location, perimeter, duration and suppression operations were determined from fire reports made by the Regional Forest Service (Servizi Forestali Regionali del Veneto). We integrated the official information collecting photos and interviewing firefighters and incident commanders who worked on the fires. Most of the fires are small because of the typical regional fire regime with few big fires and many very small fires (chapter 1). The small fires are anyway useful for fuel modelling because they represent the typical fires in the area.

The forest fires simulated in LL are the following:

- **Vendevolo** occurred on the north side of Monte Vendevolo hill, in a chestnut coppice where some forestry works were ongoing. It started from the side of an unpaved road where some residues were piled. It initially burned intensely then spread as a slow surface fire. Since the fire started at dusk no interventions were possible until dawn. It burned a steep hillside, the slope was between 30° and 40°. On the second day, ground forces and a helicopter easily suppressed the fire. At ignition time, temperature was 26 °C and relative humidity (RH) was 69%. The wind was 10 km/h from the north-east and increased during the night (Figure 3.5, 3.12).
- **Grande** occurred at the foot of Monte Grande hill north side. The hillside is covered by chestnut forest in conversion from coppice to high forest. The hillside was quite homogeneous with a slope of 30°. There were forestry works going on in the forest. The ignition was just before dusk so suppression was possible only on the back of the fire and it spread freely during the night. It burned quite intensely in the night because the vegetation was very dry due to an extreme drought in summer 2003 (ARPAV 2016). Intensive suppression began at dawn by ground forces, a helicopter and two Canadair. The ARPAV meteorological radar is on the top of Monte Grande hill, so the main suppression efforts were to avoid damage to the radar. Weather data recorded by Teolo weather station (located on the other side of Monte Grande) reported a temperature of 26 °C and RH 75% at ignition time, and the RH then increased to 90% during the night. Using the reported values of RH in the simulations, fire spread was not possible during the night. The only way for a fire to spread with such a high RH was to use a humidity of extinction over 35%. This value is much higher than that reported in the literature for temperate broadleaved forest (usually 20-25%). We decided to reduce RH to 70% in the simulation, in order to allow at least a slow fire spread during the night, as reported by a witness. This situation was probably due to the extreme drought in summer 2003 (ARPAV 2016). Wind speed was 5.7 km/h from the north (Figure 3.2, 3.13).
- **Rua** was ignited by an arsonist on the south side of Monte Rua hill, close to a secondary road. The fire initially appeared to be easy to suppress and by evening it was almost suppressed. Then at 23:15, the fire restarted from a new ignition with high intensity. Because of darkness

suppression started at dawn, so the fire spread freely during the night. From 7:00 the suppression effort became very intensive using five helicopters and one Canadair. The area had a very varied topography and vegetation, including farmland, coppices, high forests of broadleaves and softwoods. Slope varied between 20° and 35°. There is an old monastery at the top of Monte Rua that was at risk from the fire. Summer 2003 was one of the hottest and driest summers ever recorded in the region (ARPAV 2016), at ignition; temperature was 29 °C and RH 24%. During the night, RH never went above 67%. Wind speed was 4.6 km/h from the south-east (Figure 3.3, 3.4, 3.14).

- **San Giusto** was ignited by an arsonist in a *Pinus pinaster* Aiton plantation located on fossil dunes, in the town of Porto Viro. The area is flat and is used as an urban park. The canopy cover was very varied and, where the forest was not full density, the undergrowth was a tall and dense layer of *Rubus* ssp. L. It was a surface fire, but because of tall shrubs, flames up to 4 m high were reported. Suppression by ground forces began almost immediately, but was difficult because of thick undergrowth. Temperature was 27 °C and RH 40%. The wind speed was 15 km/h from the south-east (Figure 3.15).
- **Cero**. An arsonist ignited the fire on Monte Cero hill. The fire started from the roadside at the edge of an orchard and spread in a coppice. The fire happened on a south-facing hillside and the slope varied from 5° to 25°. Temperature was 34 °C, RH 30% and wind speed was 7 km/h from the north-west. Fine fuels were very dry because of a seasonal drought. Suppression by ground forces began very soon. The upper part of the fire was suppressed by a helicopter (Figure 3.16).

In MA the fires are distributed over a much larger area and vary widely in size and behaviour. The simulated fires are:

- **San Mauro** was ignited by an arsonist in the middle of a steep and rocky mountain side. Suppression by ground forces was not possible, apart from in the valley bottom. On the first day two helicopters worked just a few hours before suspending the intervention because of lack of daylight. The fire therefore spread naturally until the morning of the second day. The intervention on the second day started late morning because of a dense pall of smoke. The fire burned mainly abandoned pastures and scattered vegetation on rocky walls. It moved fast downhill because of embers falling down from the rocky walls. Fine fuels were very dry because of a foehn wind blowing on the days before the fire (Figure 3.6, 3.7, 3.17).

- **La Muda** started in a *Pinus silvestris* L. plantation on a very steep mountainside, it was ignited by a tree falling on a power line probably due to a strong gust of wind. In the first half hour, it had extreme behaviour with an active crown fire and flames 30 m high. It reached the top of mount Cartifai in less than half an hour (700 m difference in height). After that, it was mainly a surface fire. The first firefighters arriving on the site just 15 minutes after ignition did not record a strong wind, so probably there was just an isolated gust that boosted the initial fire. The landscape was very complex: there were steep mountainsides, rocky walls and deep canyons. The vegetation was very varied, it included softwood forest and shrubland, hardwood forest and shrubland, natural grassland and sparse vegetation on rocky walls. Ground forces worked only on the back side of the fire because of very dangerous working conditions. Two helicopters and two air tankers then suppressed the other sides (Figure 3.8, 3.9, 3.18).

- **Costo** was a very fast fire, mainly of grass on a steep mountain flank. It burned on the west side of Asiago Plato, where the Costo state road goes up with several hairpin bends. The fire easily crossed the road five times. The fire was ignited by an arsonist close to the road, in an area of shrubs and grass. Former pastures, long abandoned, mainly covered the mountainside. Because of several previous fires and very poor soil they never developed into a real forest. The vegetation was mainly cured tall grass with scattered shrubs and trees. The fire was very fast but with low intensity. From the photos, we measured a spread rate of 10 m/min in the central part of the fire. Temperature was 6 °C and RH 15% due to a foehn wind. Winter 2012 had very little rain. The last rainfall before the fire was of 10 mm on January 2nd. Wind speed was 5.4 km/h from the north (Figure 3.10, 3.11, 3.19).

- **Grumello** was ignited by an arsonist immediately at the end of Costo fire that was just 10km away. The crews working on the Costo fire immediately moved to the Grumello fire, so the intervention was quite fast. It had three ignition points along a forest road. The forest was a typical hop hornbeam coppice (*Ostrya carpinifolia* Scop., *Fraxinus ornus* L., *Quercus pubescens* Will.) quite rich in litter and low shrubs (mainly *Rubus* spp.). It spread on a homogenous vegetation and topography, so we could calculate the rate of spread. We estimated an average rate of spread of 2 m/min. At ignition time, temperature was 6 °C and RH 39%. Wind was 3.4 km/h from the north-east (Figure 3.20).

- **Paladini** fire burned a young coppice, very rich in *Rubus* spp. shrubs. Because of tall shrubs and steep terrain, there were tall flames (7m) and the fire spread quite fast. The mountainside was steep, so ground forces suppressed only the back side of the fire, and then a helicopter and an air tanker suppressed the other sides. Temperature was 20 °C and RH 22%. The wind speed was 3.8 km/h from the north-west (Figure 3.21).

Figure 3.2 – Grande

Figure 3.3 – Rua

Figure 3.4 – Rua

Figure 3.5 – Vendevolo

Figure 3.6 – San Mauro

Figure 3.7 – San Mauro

Figure 3.8 – La Muda

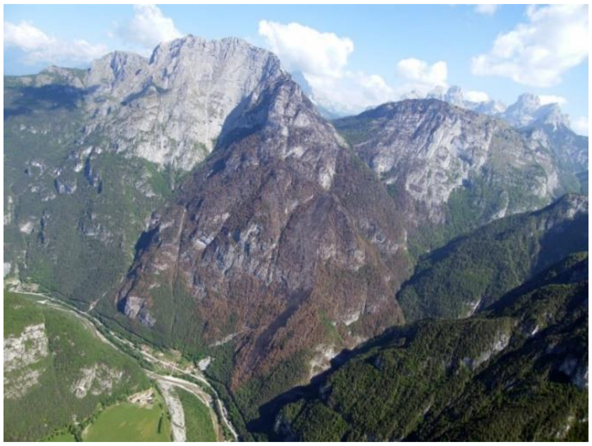


Figure 3.9 – La Muda

Figure 3.10 – Costo

Figure 3.11 – Costo

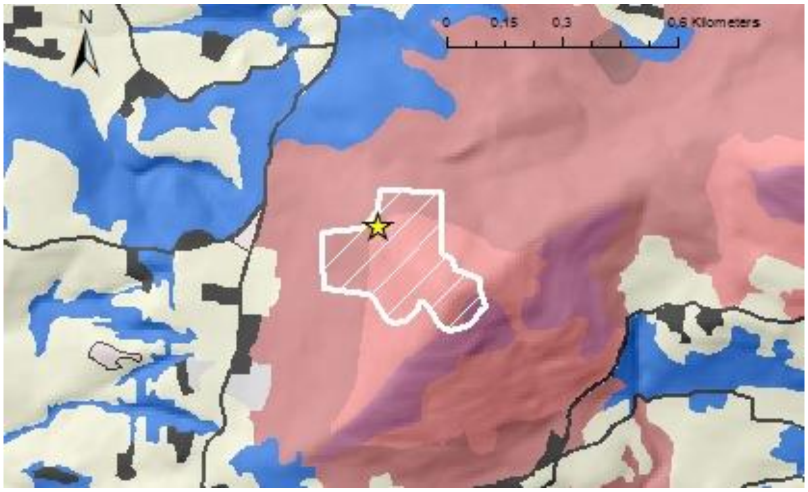


Figure 3.12 – Vendevolo map

Figure 3.13 – Grande map

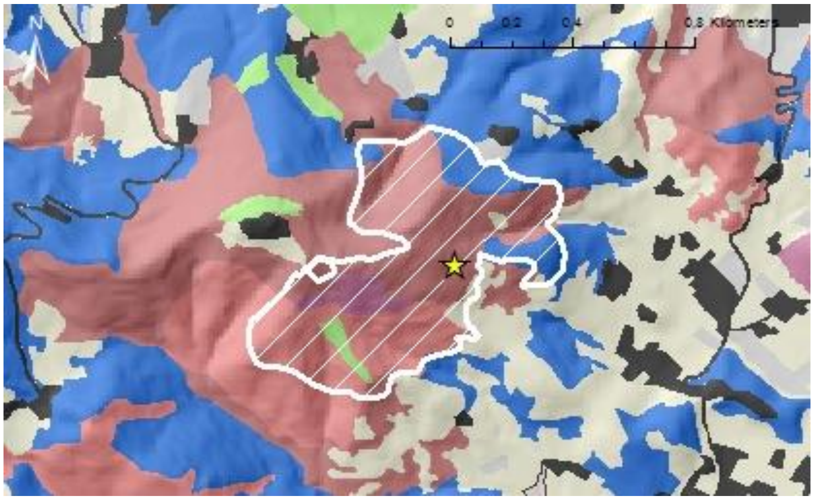


Figure 3.14 – Rua map

Legend

★ Ignition

▭ Burned area

Fuel classes

FUEL_1

- ⬜ hardwoods
- 🟪 maple, ash, lime-tree
- 🟪 black alder
- 🟪 green alder
- 🟪 birch
- 🟥 chestnut
- 🟫 oak
- 🟧 beech high elevation
- 🟧 beech meedle elevation
- 🟧 beech primitive forest
- 🟨 beech low elevation
- 🟦 hardwood plantations
- 🟦 locust tree
- 🟦 coastal forest
- 🟦 holm oak
- 🟪 willow
- 🟥 oak and mediterranean shrubs
- 🟥 hop hornbeam, holm oak
- 🟥 hop hornbeam primitive
- 🟧 hop hornbeam
- 🟥 oak, hop hornbeam
- 🟪 common hornbeam
- 🟪 oak, common hornbeam
- 🟩 fir
- 🟩 softwood platations
- 🟩 larch primitive
- 🟩 larch
- 🟩 larch, pine
- 🟩 spruce high elevation
- 🟫 spruce middle elevation
- 🟨 spruce low elevation
- 🟩 scots pine
- 🟩 scots pine sud alps
- 🟩 scots pine inner alps
- 🟫 scots pine primitive
- 🟫 spruce, beech
- 🟪 alpine farm
- 🟪 maquis
- 🟩 dwarf pine
- 🟨 dune vegetation
- ⬜ sparse vegetation
- ⬜ burned area
- 🟦 swamp vegetation
- 🟨 reed
- 🟨 igrofile vegetation
- 🟨 coastal grassland
- 🟨 sandbank
- ⬜ agricolture burnable
- 🟩 grassland
- ⬛ urban
- ⬜ agricolture
- ⬜ snow and ice
- 🟦 water
- ⬛ rock and sand

Figure 3.15 – San Giusto map

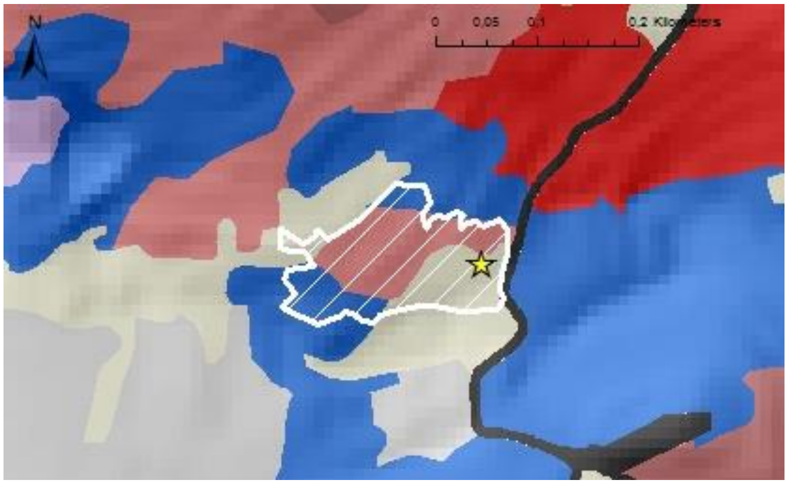


Figure 3.16 – Cero map

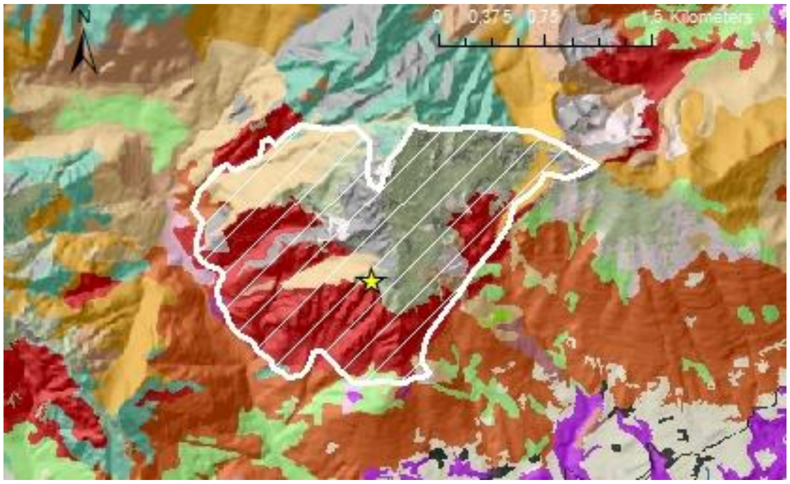
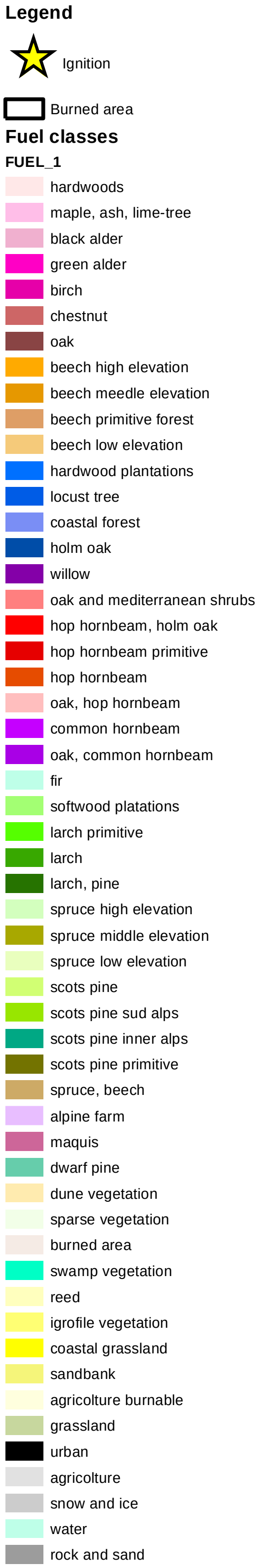


Figure 3.17 – San Mauro map



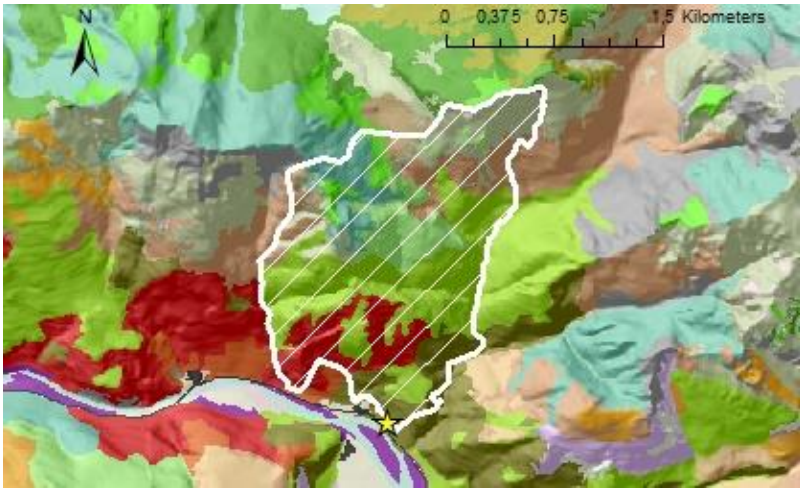


Figure 3.18 – La Muda map

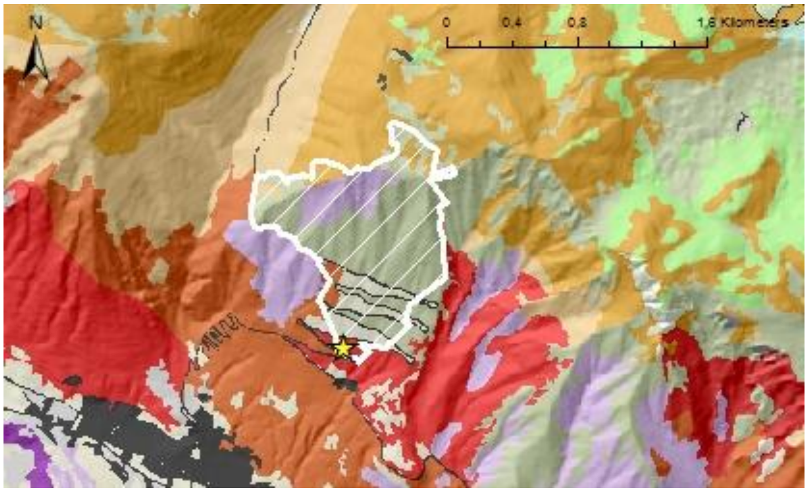


Figure 3.19 – Costo map

Figure 3.20 – Grumello map

Legend

★ Ignition

☐ Burned area

Fuel classes

FUEL_1

hardwoods
maple, ash, lime-tree
black alder
green alder
birch
chestnut
oak
beech high elevation
beech meedle elevation
beech primitive forest
beech low elevation
hardwood plantations
locust tree
coastal forest
holm oak
willow
oak and mediterranean shrubs
hop hornbeam, holm oak
hop hornbeam primitive
hop hornbeam
oak, hop hornbeam
common hornbeam
oak, common hornbeam
fir
softwood platations
larch primitive
larch
larch, pine
spruce high elevation
spruce middle elevation
spruce low elevation
scots pine
scots pine sud alps
scots pine inner alps
scots pine primitive
spruce, beech
alpine farm
maquis
dwarf pine
dune vegetation
sparse vegetation
burned area
swamp vegetation
reed
igrofile vegetation
coastal grassland
sandbank
agricolture burnable
grassland
urban
agricolture
snow and ice
water
rock and sand

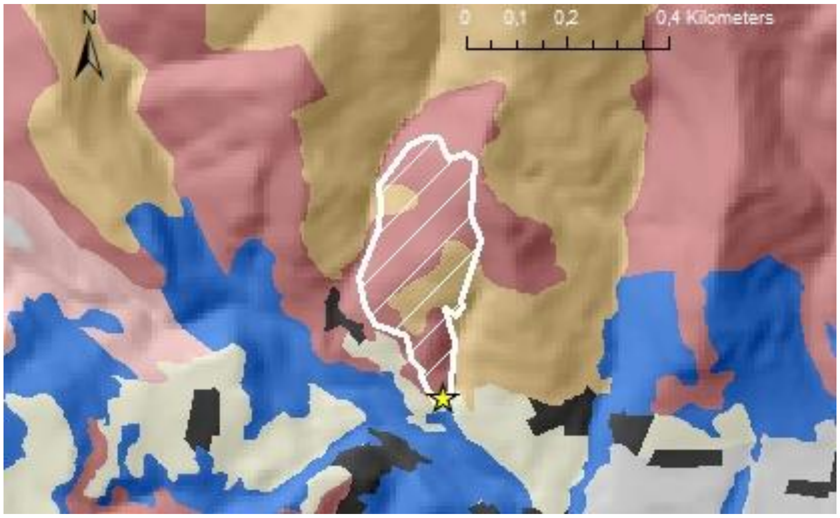


Figure 3.21 – Paladini map (Legend in the previous page)

Fuel map building

In 2007 Veneto Region Administration published a land use map covering the whole region (Veneto 2016). The map was produced by photogrammetry and has a nominal scale of 1:10000. On the map, forests are classified based on a very detailed local forest types classification (Del Favero *et al*. 2004, Del Favero 2006) of the main forest species. Since the forest type classification is too detailed for fire behaviour use, we aggregated the forest types very similar to each other in order to have fewer forest types. From the aggregation process, we obtained 43 simplified forest types. Not all types are found in the case study fires. We did not consider forest types not found in case studies in the custom fuel models building process. The links between forest types map and fire behaviour fuel models were based on the results in Chapter 2.

The case studies included all the forest types studied in Chapter 2 (Table 2.1) and some small areas of not studied forest types. We gave these forest types the same fuel model as the most similar studied forest type.

In the case of forest type set, we directly associated the fuel models to the corresponding forest types. In the cases of Prometheus and Cluster sets, a direct linkage is not possible because the forest map does not have data on forest structure. In these cases we connected forest map and fuel based on the forest structure and fuel load found in the sampling plots (Chapter 2, Tables 2.4 – 2.6).

FARSITE simulations

Simulations of the spatial and temporal spread of the fires were done using the FARSITE Fire Area Simulator model (Finney 2004). FARSITE model describes fire spread as a function of relationships between fuels, terrain and weather conditions. Data to run the model consist of a set of spatial and non-spatial files that define the physical setting, fuel availability and flammability, and climatic factors (Finney 2004). The physical setting is defined by three spatial files of elevation, slope and aspect. Two spatial files of fuel availability: canopy cover and fuel model, are required to model fires spreading in fuels along the ground. To model crown fires, spatial files of high forest height, canopy base height, and canopy bulk density are also needed. In addition to spatial data, FARSITE also requires a weather file, wind file, optional fuel moisture adjustments and spread rate adjustments.

The grid resolution of all the spatial information was 25 m. We used the Veneto Region digital elevation model (DEM) to produce the maps of elevation, slope and aspect.

In urban areas, water, rocks and farmland were given the non-burnable fuel models (Scott and Burgan 2005), apart from pastures and permanent fields that in most simulations were considered as burnable area. Using the conversion file option, we gave every forest type reported on the fuel map, a fuel model from the fuel file. The fuel file changed at every simulation according to the tested fuel models set.

We assigned canopy cover based on the Veneto Region forest map (Veneto 2016) with some corrections in the area where there were evident changes in canopy cover due to previous fires or wood utilization.

In the studied forest types we produced the high forest height map based on high forest height recorded in the sampling (Chapter 2). In the other forest types, we used the average values reported by Del Favero (2004). In La Muda and Vendevolo case studies the high forest height was corrected based on field survey and photo interpretation in order to have a more realistic value.

Canopy base height was assigned as unique value to every fuel model based on average values recorded in similar forest types (Chapter 2) and the values were then corrected in any areas showing very different conditions from the average (e.g. La Muda).

We did not directly measure the crown bulk density (CBD) in the study area, so we had to use average data from other studies. In LL we gave a low value (0.1 kg/m3) to hardwood forests in order to simulate the very low possibilities of a crown fire. In MA area we gave the value of 0 kg/m^3 to hardwood forests because the case study fires happened in winter, when most trees do not have leaves. In most softwood forests, we gave the value of 0.18 kg/m^3 to CBD that is an average value found in the literature for similar forests (Fernández-Alonso *et al*. 2013, Keane et al. 2012, Mitsopoulos and Dimitrakopoulos 2014, Riano *et al*. 2003, Scott and Reinhardt 2005). In *Larix decidua* Mill. forest, and in *Pinus mugo* Turra forests we fixed the CBD at 0.1 kg/m^3 because the density is lower than an average pine forest.

Since no information was available about fuel moisture during case study fires, we determined the initial 1H fuel moisture using Behave plus 5.0.5 fine dead fuel moisture content tool (Andrews 2009). Then we used the 1H fuel moisture as input for selecting 10H, 100H, live wood and live herbs moisture based on the most suitable fuel moisture scenario (Scott and Burgan 2005).

All the weather data (temperature, relative humidity, rainfall, wind speed and direction) were obtained from the weather stations of the Regional Agency for Environmental Protection (ARPAV). In every fire, we selected the most representative weather station for the fire area. In some cases, we averaged the value of two stations. In three fires (La Muda, Grande, Costo) the wind speed and direction recorded by weather stations were not representative of real conditions, so we fixed a value based on interviews, photos of smoke plume and fire behaviour.

We spatialized wind speed and direction using Windninja (Forthofer and Butler 2015). In every case study, we created a wind map for the day before the fire, a map at ignition time and then during the fire we produced a new wind map at every significant change in wind speed or direction. We also then created a map for the day after the fire. The main simulation parameters are reported in Table 3.2.

Each simulation produced the following outputs: Time of arrival, Burned area, Fire perimeter, Fire line intensity, Rate of spread, Flame height, Heat/area, Crown fire activity, Spread direction and Reaction intensity.

We did not use the adjustment tool in FARSITE.

Table 3.2 – Main simulation parameters

Simulation			**Moisture content %**					**Temp. C°**		**R.H. %**		**Wind**	
Case study	**start**	**Duration (h)**	**1H**	**10H**	**100H**	**live herbs**	**live shrubs**	**min.**	**max.**	**max.**	**min.**	**speed (kmh^{-1})**	**direction (deg)**
Vendevolo	13/07/2003 21:15	9:30	13	14	15	60	90	20	33	96	46	9	68
Grande	15/08/2003 21:00	10	12	13	14	30	60	20	30	70	47	2	23
Rua	21/09/2003 15:25	17:30	6	7	8	30	60	18	30	63	23	3	158
San Giusto	10/05/2012 16:00	2	6	7	8	90	120	10	25	94	40	11	101
Cero	03/08/2012 14:15	2	5	6	7	60	100	24	34	65	29	7	338
San Mauro	06/02/2011 13:00	24	3	4	5	30	60	8	13	19	11	1	210
La Muda	10/05/2011 13:43	18	5	6	7	30	60	5	15	72	36	30	170
Costo	25/01/2012 10:30	9:30	14	15	16	30	60	-7	7	77	17	1	186
Grumello	26/01/2012 14:00	3	6	7	8	60	90	-2	6	77	33	0	251
Paladini	30/03/2012 11:00	7	5	6	7	90	100	14	21	33	22	2	110

Fire behaviour fuel models

In addition to the custom fire behaviour fuel models sets developed in chapter 2 (Forest type, Prometheus, Cluster; Table 2.18), we also tested the use of Standard fire fuel models and the calibration of custom fuel models in order to obtain more realistic simulations.

Standard fire behaviour fuel models (Standard) - We linked every forest type found on case study maps with one of the 53 Standard fuel models (Anderson 1982, Scott and Burgan 2005). We selected Standard fuel models based on: the average fuel load of every forest type (Chapter 2, Table 2.6), the typical fire behaviour recorded in the forest types and fire simulation accuracy in the case study simulations (Table 3.3).

Table 3.3 – Main parameters of utilized Standard fire behaviour fuel models (Anderson 1982, Scott and Burgan 2005)

Description	Code	Fuel model code	1H t ha^{-1}	10H t ha^{-1}	100H t ha^{-1}	Live herb t ha^{-1}	Live woody t ha^{-1}	1n area/vol ratio cm^{-1}	Herbs area/vol ratio cm^{-1}	Live woody area/vol ratio cm^{-1}	Fuel Bed Depth m
Timber grass and understory	FM2	4.49	2.25	1.12	1.12	0.00	99	50	-	0.30	15
Brush	FM5	2.25	1.12	0.00	0.00	4.49	66	-	50	0.61	20
Dormant brush	FM6	3.37	5.62	4.49	0.00	0.00	58	-	-	0.76	25
Compact timber litter	FM8	3.37	2.25	5.62	0.00	0.00	66	-	-	0.06	30
Hardwood litter	FM9	6.54	0.93	0.34	0.00	0.00	83	-	-	0.06	25
Timber litter and understory	FM10	6.74	4.49	11.23	0.00	4.49	66	-	50	0.30	25
Short. sparse dry climate grass	GR1	0.22	0.00	0.00	0.67	0.00	73	66	-	0.12	15
Low load dry climate grass	GR2	0.22	0.00	0.00	2.24	0.00	66	59	-	0.30	15
Moderate load humid climate grass-shrub	GS3	0.67	0.56	0.00	3.25	2.80	59	52	52	0.55	40
Moderate load humid climate shrub	SH3	1.01	6.73	0.00	0.00	13.90	52	-	46	0.73	40
Moderate load humid climate timber-grass-shrub	TU3	2.47	0.34	0.56	1.46	2.47	59	52	46	0.40	30

Calibrated fire behaviour fuel models (Calibrated)

The calibration process iteratively adjusts fuel model parameters based on their performance against observed rate of spread or flame height (Burgan and Rothermel 1984, Cai *et al.* 2014, Rothermel 1983). This is usually done by starting from either Standard fuel models, or mean or median characteristics of sampled fuelbeds, followed by subjective adjustments until a satisfactory match is achieved between predictions and observations (Burgan 1987, Cruz and Alexander 2010).

We selected the fuel models that had the highest accuracy in burned area simulation and adjusted fuel model inputs to match observed fire behaviour. We chose to calibrate forest type models because they are the most adapt to be linked to a regional forest map and the modifications needed were quite evident. We mainly modified fuelbed height because that was the limiting factor in most of the fuel models. We increased the fuelbed height in order to have faster fire spread and higher flames when the models underestimated the real fire behaviour.

Statistical analysis

We assessed the influence of fuel models on the accuracy of simulated fire spread and behaviour for all the case studies. An error matrix between observed and simulated fire perimeters was calculated to define the frequency of each case (presence/absence of burned area). Sørensen's coefficient (SC) (Legendre and Legendre 1998) and Cohen's kappa coefficient (K) (Congalton 1991) were used as measures of the spatial accuracy of the extent of simulated fire spread (Arca *et al*. 2007b, Salis 2008). Sørensen's coefficient was used as indicator of the exclusive association between observed and simulated burned areas. SC values were calculated as follows:

$$SC = \frac{2a}{2a+b+c}, \tag{3.1}$$

Where a is the number of cells coded as burned in both observed and simulated data (burned area agreement), b is the number of cells coded as burned in the simulation and unburned in the observation (modelling overestimation) and c is the number of cells coded as unburned in the simulation and burned in the observation (modelling underestimation) (Arca *et al*. 2007b).

Kappa statistics compute the frequency with which the simulated area agrees with the observed data, with an adjustment that takes into account agreement by chance (Filippi *et al*. 2014). K values were calculated as follows (Cohen 1960):

$$K = \frac{p_0 - p_e}{1-p_e} = 1 - \frac{1-p_0}{1-p_e} \tag{3.2}$$

Where p_o is the relative observed agreement among raters, and p_e is the hypothetical probability of chance agreement, using the observed data to calculate the probabilities of each observer randomly saying each category.

Both K and SC coefficient values typically range between 0 and 1, with values close to 1 indicate very high spatial agreement between simulated and observed fire perimeters (Arca *et al*. 2007b). Following Landis and Koch (1977), the interpretation of kappa values is provided in Table 3.4.

Table 3.4 – Interpretation of K values

Kappa range	Interpretation
<0	No agreement
0.0 – 0.2	Slight agreement
0.2 – 0.4	Fair agreement
0.4 – 0.6	Moderate agreement
0.6 – 0.8	Substantial agreement
0.8 – 1.0	Almost perfect agreement

Moreover ArcMap 10.3 was used to analyze and summarize the fire behaviour data (ROS, FLI, FML).

Fire behaviour comparison

We did not use statistical indices to compare fire behaviour among simulations because the observed fire data in this data set contain an unknown level of error that varies spatially, temporally, and between fires. This is a common problem in any attempt to validate fire behaviour models using wildfires. The pervasive lack of control over input data precluded any attempt to perform a rigorous validation of fire behaviour models (Finney 2000). The process of testing the usefulness of a fire growth model has traditionally involved visual comparisons between the observed and predicted fires. This is a practical measure that will always be used when models are exercised operationally (Finney 2000).

Based on comparison between reported and simulated fire behaviour outputs (flame height, rate of spread, burned area, main spread direction), we defined an agreement threshold between simulated and observed fires. The possible scores are: A) Realistic, simulation gives a good approximation between reported and simulated fire behaviour; B) Quite realistic, simulation partially matches reported fire behaviour; C) Not realistic, simulation completely does not match reported fire behaviour.

Results

Standard fire behaviour fuel models (Anderson 1982, Scott and Burgan 2005)

In most of the forest types, we found a good correspondence between observed and simulated fire behaviour made by Standard fuel models 8, 9 and 10. The only exceptions are in the primitive Scots pine forest where we associated model 6; the dwarf pine forest where model 5 had the more realistic fire spread, and primitive hop hornbeam where we chose TU3 due to the high amount of grass and shrubs. In shrubland models 4, 5 and 6 simulated too high flames and a too fast rate of spread compared with observed. We selected models with lower rate of spread and flame height: GS3 where grass is the main fuel and SH3 where shrubs are the main fuel. In the case of not mown grassland, model 1 was generally burning too fast compared with observed, so we chose model GR2. Furthermore, GR2 has similar herbs load to that measured in Chapter 2 (Table 2.6). We used GR1 in the land use where fire spread is very limited: farmland, mown fields, and sparse vegetation. The parameters of utilized Standard fuels models are reported in Table 3.3.

Fuel map association

All the fuel models were linked to the fuel map, as reported in Table 3.5. In the case of dwarf pine forest and sparse vegetation, we could not make a representative fuel model based on the collected data (Chapter 2, Table 2.6), so we always used the Standard fire fuel model 5 (Anderson 1982). We separated farmland in burnable and not burnable. We considered orchards and grassland as burnable, because, in some case studies, they burned during the fire because the grass was not mown. In LL, we considered the burnable farmland like fire fuel model GR1 when the grass was short because recently mowed, otherwise we gave farmland the fire fuel model GR2. Unlike than on the forest map, we separated Mediterranean pine plantations (*Pinus pinaster, Pinus pinea* L.) from the other softwood plantations because they had more litter and shrubs than the ones on the Colli Euganei.

Non-burnable fuel models (NB) were assigned to most farmland and to roads, buildings, urban areas, water bodies and bare ground.

Table 3.5 – Linkage between simplified forest types (Del Favero 2006) and fuel model sets

Forest type	LL					MA				
	Forest type	**Prometheus**	**Cluster**	**Standard**	**Calibrated**	**Forest type**	**Prometheus**	**Cluster**	**Standard**	**Calibrated**
new hardwoods forest	LNA	LP3	LC4	FM6	LF3	MNA	MP2	MC3	FM10	MF3
chestnut	LCH	LP6	LC3	FM10	LF1	MCH	MP6	MC2	FM10	MF1
oaks	LHO	LP5	LC2	FM8	LF2					
beech high elevation						MHO	MP5	MC1	FM8	MF2
beech middle elevation						MHO	MP5	MC1	FM8	MF2
beech primitive forest						MHO	MP2	MC1	SH3	MF2
beech low elevation						MHO	MP6	MC3	FM9	MF2
locust tree	LHO	LP6	LC2	FM9	LF2	MHO	MP5	MC1	FM8	MF2
oaks and Mediterranean shrubs	LCH	LP6	LC3	FM10	LF1					
hop hornbeam, holm-oak	LHO		LC4	FM5	LF2	MHO	MP6	MC2	FM10	MF2
hop hornbeam primitive						MHO	MP2	MC3	TU3	MF2
hop hornbeam						MHO	MP6	MC2	FM10	MF2
oaks, hop hornbeam						MHO	MP5	MC1	FM10	MF2
common hop hornbeam						MHO	MP5	MC1	FM8	MF2
oaks - common hop hornbeam						MHO	MP5	MC1	FM8	MF2
softwoods plantation	LSP	LP5	LC1	FM9	LF4	MSP	MP6	MC2	FM9	MF4
larch primitive						MSP	MP2	MC3	FM2	MF4
Scots pine south Alps						MSP	MP6	MC2	FM10	MF4
Scots pine primitive						MSP	MP7	MC3	FM6	MF4
spruce, beech						MSP	MP6	MC1	FM8	MF4
shrubland	LNA	LP3	LC4	FM6	LF3	MNA	MP3	MC2	GS3	MF3
maquis	LNA	LP3	LC4	FM6	LF3					
dwarf pine						FM5	FM5	FM5	FM5	FM5
sparse vegetation						GR1	GR1	GR1	GR1	GR1
Mediterranean pine	LSP	LP7	LC4	FM10	LF4					
burnable farmland	GR*	GR*	GR*	GR*	GR*	MGR	MP2	MC3	GR1	MF5
pasture						MGR	MP2	MC3	GS2	MF5

* Gr1 or Gr2 based on local situations

Fire simulation accuracy

In all the case studies, we compared simulated and observed fire perimeters separately in LL study area (Figure 3.22 – 3.26, Table 3.6) and in MA study area (Figure 3.27 – 3.31, Table 3.7).

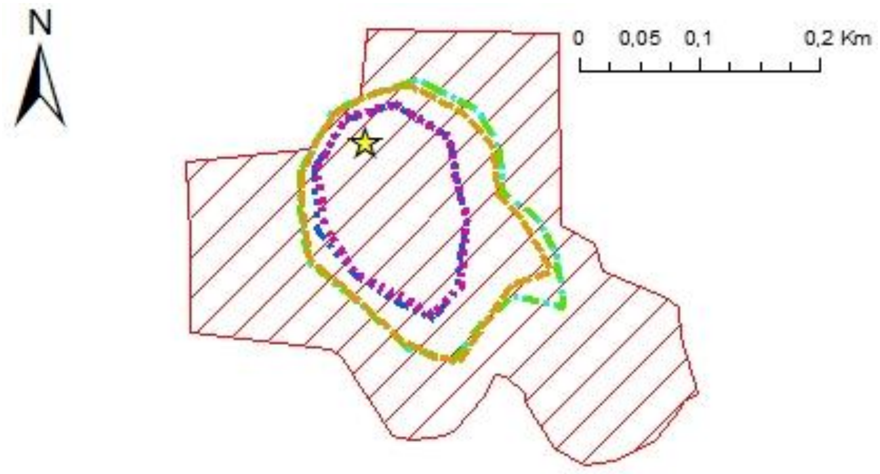
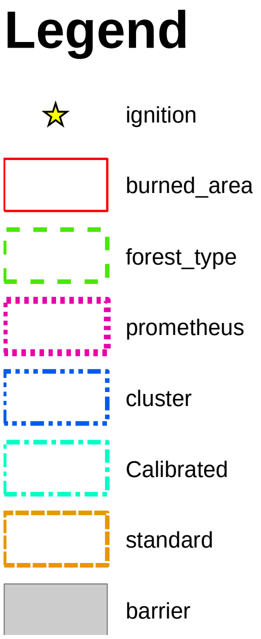


Figure 3.22 – Vendevolo simulations



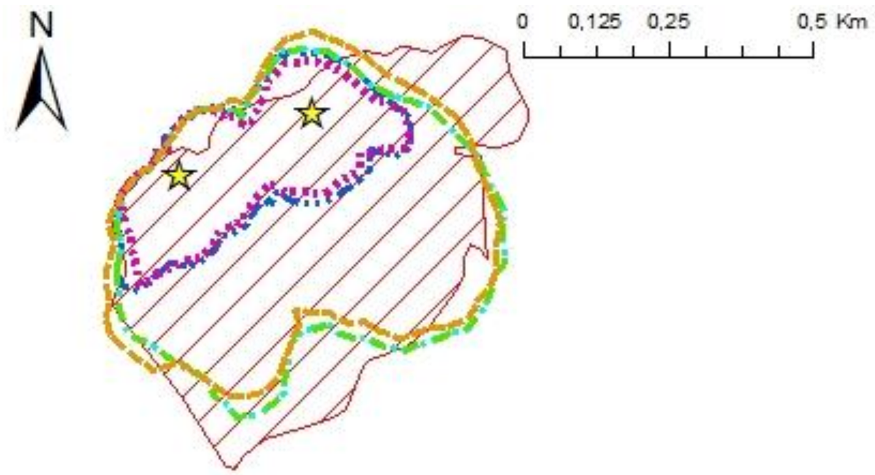


Figure 3.23 – Grande simulations

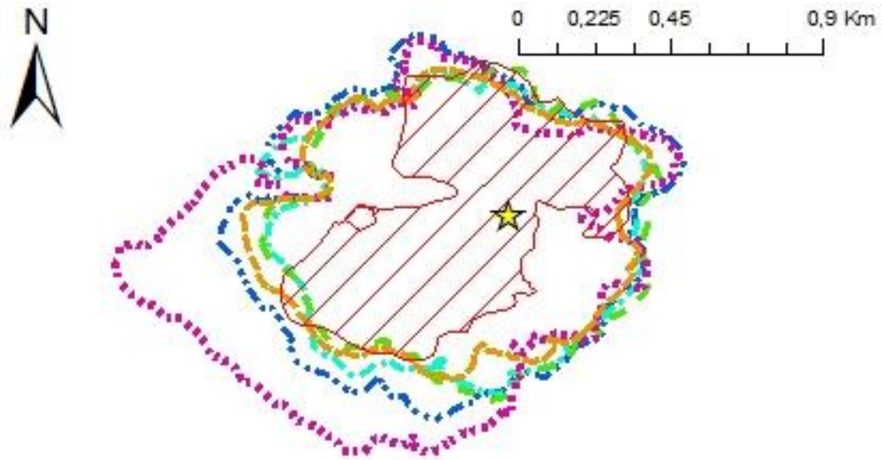
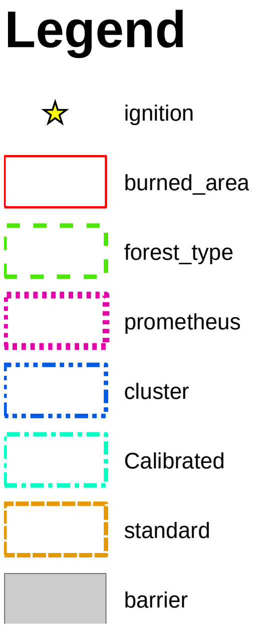


Figure 3.24 – Rua simulations



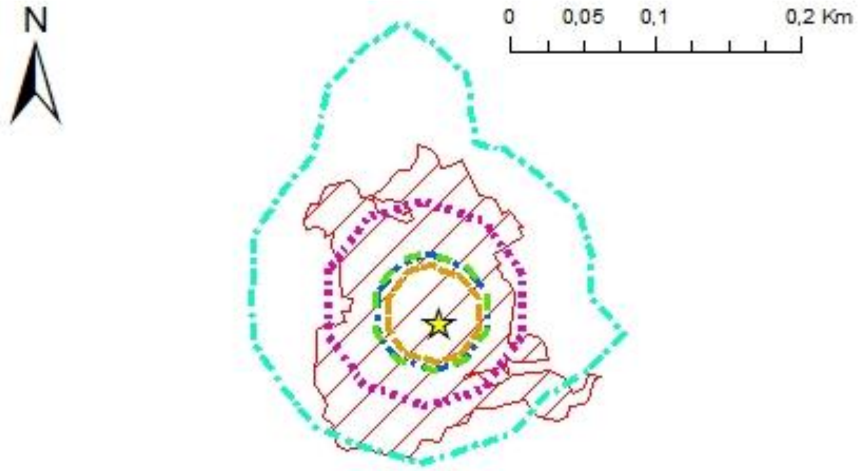


Figure 3.25 – San Giusto simulations

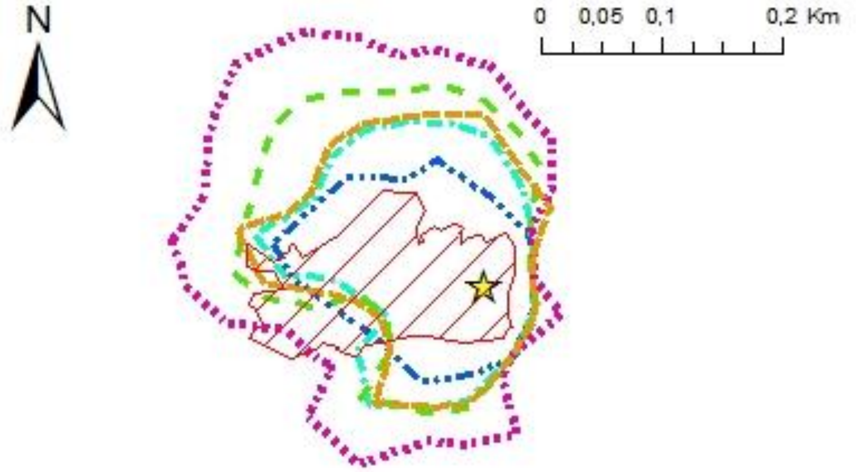


Figure 3.26 – Cero simulations

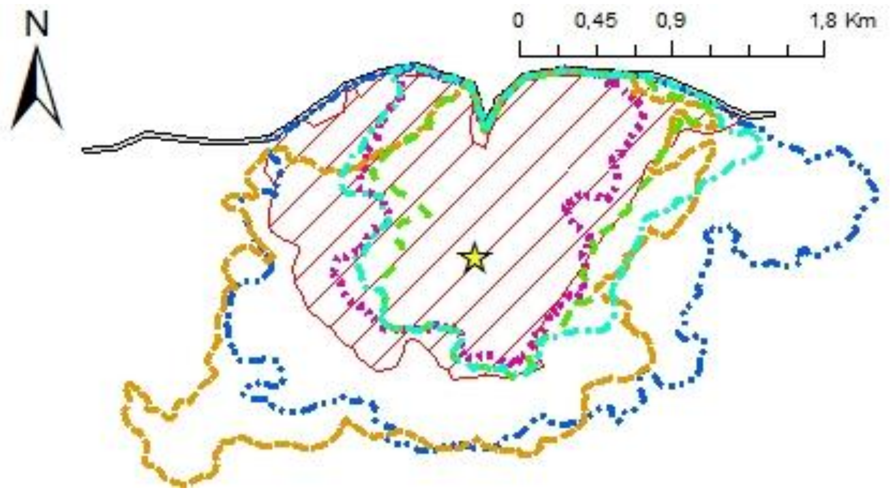
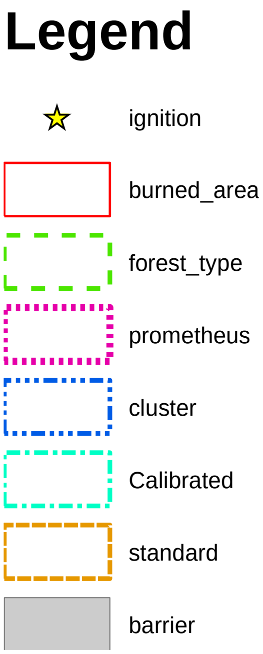


Figure 3.27 – San Mauro simulations



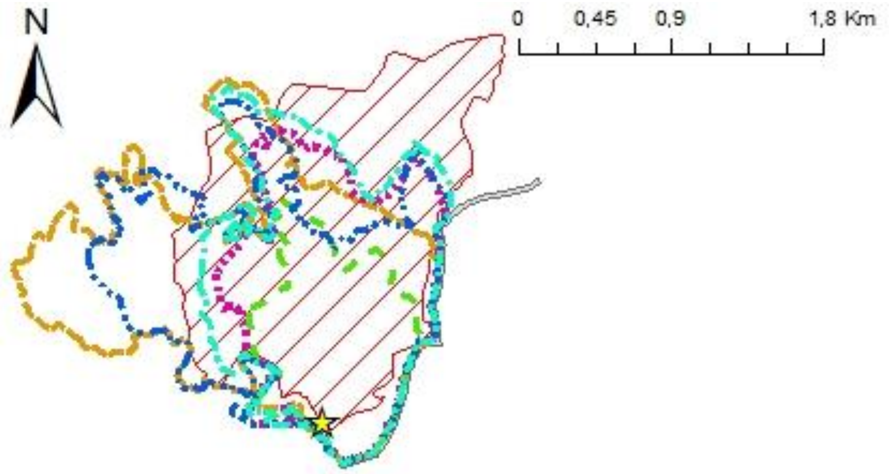


Figure 3.28 – La Muda simulations

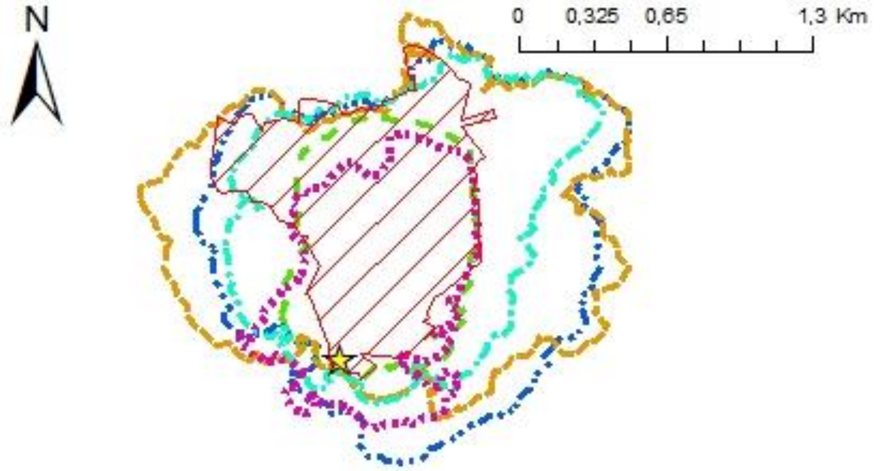


Figure 3.29 – Costo simulations

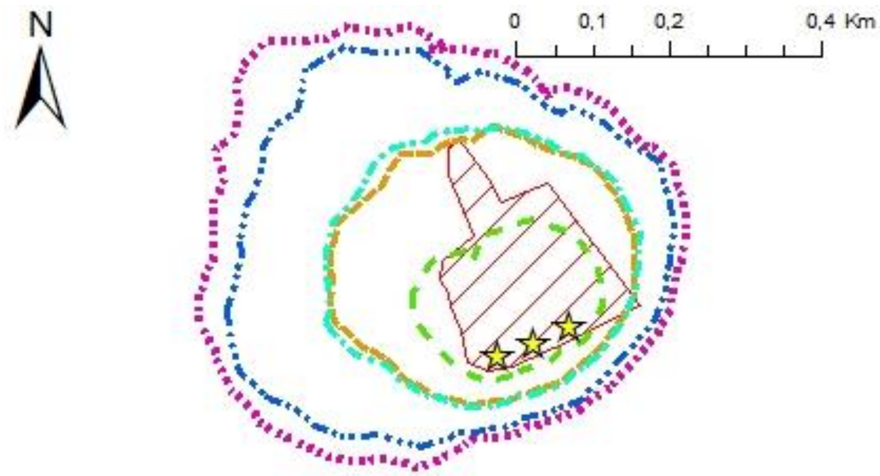
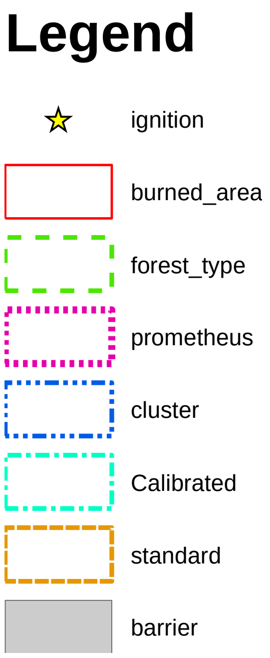


Figure 3.30 – Grumello simulations



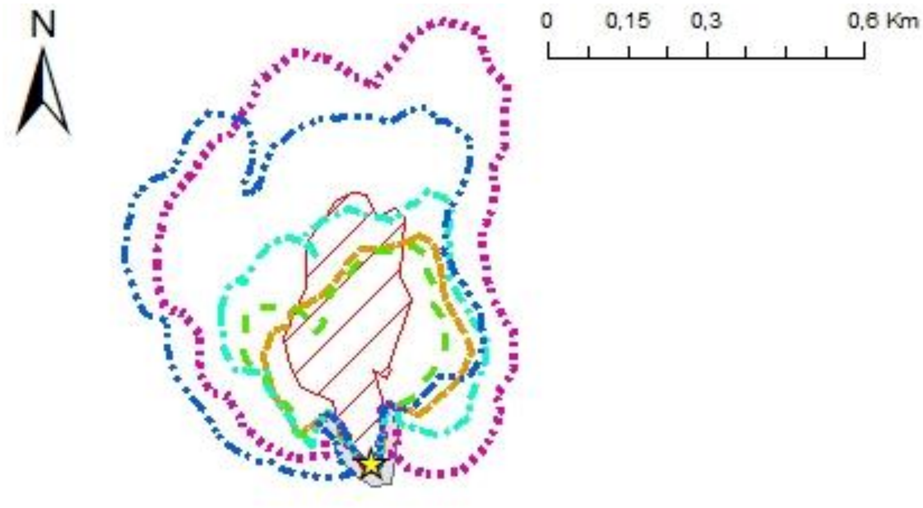


Figure 3.31 – Paladini simulations

Table 3.6 - LL **-** Statistical evaluation of FARSITE performances for different combinations of fire behaviour fuel models. In bold the set with higher SC and K values**.**

Case study	F.M. set	Fuel model code	SC[1]	K[2]	A[3] (ha)	B[4] (ha)	C[5] (ha)
Vendevolo	**Forest type**	**(LHO, LCH)**	**0.49**	**0.48**	**3.00**	**0.06**	**6.06**
	Prometheus	(LP3)	0.31	0.30	1.69	0.00	7.38
	Cluster	(LC3)	0.31	0.30	1.69	0.00	7.38
	Standard	(FM10)	0.49	0.47	2.94	0.06	6.13
Grande	**Forest type**	**(LCH, GR1)**	**0.84**	**0.82**	**25.06**	**2.56**	**7.06**
	Prometheus	(LP6, GR1)	0.38	0.34	7.88	1.00	24.25
	Cluster	(LC3, GR1)	0.40	0.36	8.56	1.63	23.56
	Standard	(FM10, GR1)	0.82	0.79	24.63	3.56	7.50
Rua	Forest type	(LHO, LCH, LSP, LNA, GR1)	0.72	0.68	45.13	32.63	2.13
	Prometheus	(LP3, LP5, LP6, LP7, GR1)	0.56	0.49	43.69	66.25	3.56
	Cluster	(LC1, LC2, LC3, LC4, GR1)	0.65	0.60	46.50	48.75	0.75
	Standard	**(FM6, FM9, FM10, GR1)**	**0.73**	**0.70**	**44.44**	**29.50**	**2.81**
San Giusto	Forest type	(LSP)	0.35	0.34	0.50	0.00	1.88
	Prometheus	**(LP7)**	**0.77**	**0.77**	**1.50**	**0.00**	**0.88**
	Cluster	(LC4)	0.35	0.34	0.50	0.00	1.88
	Standard	(FM10)	0.27	0.26	0.38	0.00	2.00
Cero	Forest type	(LHO, LCH, GR1)	0.43	0.42	1.44	3.31	0.56
	Prometheus	(LP6, LP7, GR1)	0.38	0.37	1.88	6.00	0.13
	Cluster	**(LC2, LC3, GR2)**	**0.63**	**0.63**	**1.44**	**1.13**	**0.56**
	Standard	(FM5, FM9, FM10, GR2)	0.51	0.51	1.50	2.38	0.50
Total	Forest type		2.83	2.74	-	-	-
	Prometheus		2.35	2.23	-	-	-
	Cluster		2.41	2.27	-	-	-
	Standard		2.82	2.73	-	-	-

1 Sorensen’s coefficient value; 2 Cohen’s kappa coefficient value; 3 burned area agreement between observed and modelled fire; 4 simulation overestimation; 5 simulation underestimation

Table 3.7 – MA – Statistical evaluation of FARSITE performances for different combinations of fire behaviour fuel models (in bold the set with higher SC and K values)**.**

Case study	F.M. set	Fuel model code	SC[1]	K[2]	A[3] (ha)	B[4] (ha)	C[5] (ha)
San Mauro	Forest type	(MHO, MNA, MSP, MGR, FM5, GR1)	0.76	0.71	196.1	9.9	116.1
	Prometheus	**(MP2, MP5, MP6, FM5, GR1)**	**0.83**	**0.79**	**227.4**	**11.0**	**84.7**
	Cluster	(MC1, MC2, MC3, FM5, GR1)	0.70	0.60	310.6	266.3	1.6
	Standard	(FM5, FM8, FM9, FM10, SH3, TU3, GR1)	0.68	0.57	272.6	219.6	39.6
La Muda	Forest type	(MHO, MNA, MSP, FM5, GR1)	0.51	0.47	76.4	18.3	130.1
	Prometheus	**(MP2, MP6, MP7, FM5, GR1)**	**0.72**	**0.69**	**135.4**	**32.7**	**71.1**
	Cluster	**(MC2, MC3, MC4, FM5, GR1)**	**0.72**	**0.69**	**154.1**	**65.5**	**52.4**
	Standard	(FM5, FM6, FM9, FM10, SH3, TU3, GR2)	0.69	0.65	162.5	102.1	44.0
Costo	**Forest type**	**(MHO, MNA, MGR)**	**0.75**	**0.73**	**65.5**	**11.9**	**31.1**
	Prometheus	(MP2, MP3, MP5, MP6)	0.62	0.58	55.6	27.1	41.0
	Cluster	(MC1, MC2, MC3)	0.57	0.49	91.9	132.4	4.6
	Standard	FM8, FM9, FM10, GS3)	0.56	0.48	92.6	139.8	3.9
Grumello	**Forest type**	**(WHO, WCH)**	**0.73**	**0.72**	**2.8**	**0.8**	**1.3**
	Prometheus	(MP6)	0.26	0.24	4.1	23.6	0.0
	Cluster	(MC2)	0.30	0.28	4.1	18.8	0.0
	Standard	(FM10)	0.54	0.53	4.1	6.8	0.1
Paladini	Forest type	(MHO, MCH, GR1)	0.61	0.60	5.2	4.2	2.6
	Prometheus	(MP5, MP6, GR1)	0.31	0.28	7.8	34.1	0.0
	Cluster	(MC1, MC2, MC3)	0.43	0.42	2.8	3.8	3.5
	Standard	**(FM8, FM9, GR1)**	**0.62**	**0.61**	**5.5**	**4.5**	**2.3**
Total	Forest type		3.35	3.22	-	-	-
	Prometheus		2.74	2.58	-	-	-
	Cluster		2.73	2.48	-	-	-
	Standard		3.09	2.83	-	-	-

1 Sorensen's coefficient value; 2 Cohen's kappa coefficient value; 3 burned area agreement between observed and modelled fire; 4 simulation overestimation; 5 simulation underestimation

Since the case studies were all very different in terms of orography, vegetation, fire size and behaviour, a general comparison is very difficult. No classification was the best in every situation.

In LL, the fires that burned mainly chestnut forest (Grande, Vendevolo) were well represented by Forest type (LCH), and Standard model 10 (Anderson 1982), because they had a similar fire behaviour. Accuracy is generally good (Vendevolo) or very good (Grande 2003) (Figure 3.22, 3.23; Table 3.6). In the other LL case studies the results are not so clear.

All the models underestimated Vendevolo because all of them stopped the fire propagation during the night. The best accuracy was from Forest type (S=0.49, K=0.48), Calibrated (S=0.49, K=0.48) and Standard (S=0.49, K=0.47) models (Figure 3.22).

Since it burned mainly during the night, Grande fire was badly simulated by the models that reached extinction humidity during the night (Cluster, S=0.38, K=0.34 and Prometheus, S=0.40, K=0.36). It was well simulated by the models that do not stop burning in the night (Forest type S=0.84, K=0.82 and Standard S=0.82, K=0.89) (Figure 3.23).

Rua burned mainly during the night and all the models correctly went on burning in the night, so the differences between models were very low apart from Prometheus models that had a larger burned area and the worst accuracy (S=0.56, K=0.49). The other models correctly estimated the fire size. Because of a large variety of fuels, an evaluation of the single fuel model is difficult (Figure 3.24).

San Giusto was underestimated by all the models. Prometheus was the most accurate (S=77, K=77).

Cero had low variability between simulated burned areas. The most accurate simulation was the Cluster (K=0.63, S=0.63), that is the one with the smaller burned area. The largest burned area was obtained with Prometheus set that had the lowest accuracy (K=0.38, S=0.37). The fire front was well estimated by all the classifications. The two flanks and back were correctly overestimated, since suppression started early on those sides (Figure 3.26).

In MA no classification method performed clearly better than the others in most of the simulations. Small fires tended to be overestimated in most cases, probably because of the high influence of suppression on fire perimeter (Table 3.7).

San Mauro showed a high agreement in all the simulations. Standard fuel models and Cluster models overestimated burned area. Since intervention efforts in the upper part of the fire were on the second day, the overestimation was not correct. The other models had a realistic burned area. The best accuracy was from Prometheus models (S=0.83, K=0.79) (Figure 3.27).

La Muda had a very complex landscape and fire behaviour. For this reason underhigh foresting the influence of the single fire model is difficult. All the models, apart from the Forest type, showed substantial agreement. Prometheus and Cluster models had the same accuracy (S=0.72, K=0.69). All models underestimated fire spread in the first half hour of the fire when it was an active crown fire, and slightly overestimated the fire spread the rest of the time. The result was a substantial agreement but the single stages were not perfectly represented (Figure 3.28).

Costo fire simulation strongly depended on grass models. Forest type set showed the best accuracy (S=0.75, K=0.73), but slightly underestimated fire behaviour (Figure 3.29).

Grumello had very homogenous terrain and fuels, so it was a good test for propagation in hop hornbeam forest. The Forest type set had a substantial agreement (S=0.73, K=0.72) but underestimated fire spread. Standard fuel models (S=0.54, K=0.53) had a lower agreement but perfectly simulated the fire spread at its front, so we consider them more realistic (Figure 3.30).

Paladini fire had a wide difference between simulations. Prometheus and Cluster models strongly overestimated burned area. The other models were quite similar to each other. The best agreement was with Standard fuel model (S=0.62, K=0.61) (Figure 3.31).

Fuel models and fire behaviour

The main simulations output (flame height, rate of spread, burned area, fire type) are reported in Table 3.8 for LL study area and Table 3.9 for MA study area.

In Vendevolo fire simulations, the average and maximum flame heights were always much lower than observed (simulated 0.49-0.60 m, observed 2 m). The high flames reported in the observed fire were probably due to some slash left in a pile close to the ignition point, and the fire then spread as a surface fire. Simulations had very low flames and slow spread because we did not simulate the piled residues and the fire spread mainly during the night when RH was quite high. Simulations probably overestimated the effect of night-time RH.

Table 3.8 – LL **–** Comparison of main fire parameters (flame height, rate of spread, burned area, fire type). Real = observed fire behaviour. NR = not registered

Case study	**F.M. set**	**Flame Height**			**Rate of Spread**		**Burned area (ha)**	**Fire type**
		Average (m)	**S.D. (m)**	**Maximum (m)**	**Average (m min^{-1})**	**S.D. (m min^{-1})**		
Vendevolo	Real	2.00		7.00	NR		10.00	surface
	Forest type	0.49	0.21	0.88	0.55	0.38	3.10	surface
	Prometheus	0.56	0.20	0.90	0.81	0.47	1.60	surface
	Cluster	0.65	0.24	1.11	0.83	0.45	1.40	surface
	Standard	0.60	0.28	1.06	0.59	0.43	2.80	surface
Grande	Real	1.00		3.00	NR		30.68	surface
	Forest type	0.49	0.14	0.99	0.55	0.33	21.90	surface
	Prometheus	0.33	0.14	0.68	0.35	0.22	7.60	surface
	Cluster	0.44	0.19	0.90	0.37	0.24	7.10	surface
	Standard	0.60	0.22	1.30	0.60	0.43	21.70	surface
Rua	Real	NR		NR	NR		48.00	surface / passive crown
	Forest type	0.54	0.18	1.35	0.58	0.32	74.30	surface / passive crown
	Prometheus	0.72	0.43	2.98	0.81	0.52	107.00	surface / passive crown
	Cluster	0.70	0.31	1.79	0.64	0.40	72.00	surface / passive crown
	Standard	0.60	0.25	1.67	0.57	0.38	71.00	surface / passive crown
San Giusto	Real	2.00		4.00	NR		2.30	surface
	Forest type	0.44	0.05	0.51	0.28	0.07	0.30	surface
	Prometheus	0.74	0.07	0.84	0.50	0.10	0.90	surface
	Cluster	0.52	0.05	0.58	0.28	0.06	0.30	surface
	Standard	0.48	0.05	0.55	0.28	0.05	0.30	surface
Cero	Real	1.00		1.00	NR		2.21	surface
	Forest type	0.78	0.24	1.33	1.54	0.86	2.50	surface / passive crown
	Prometheus	1.11	0.48	2.33	1.71	0.78	4.90	surface / passive crown
	Cluster	1.20	0.29	2.12	0.99	0.66	3.10	surface / passive crown
	Standard	0.64	0.17	0.94	1.26	0.77	1.80	surface / passive crown

Table 3.9 – MA – Comparison of main fire parameters (flame height, rate of spread, burned area, fire type). Real = observed fire behaviour. NR = not registered

Case study	F.M. Set	Flame Height			Rate of Spread		Burned area (ha)	Fire type
		Average (m)	S.D. (m)	Maximum (m)	Average (m min^{-1})	S.D. (m min^{-1})		
San Mauro	Real	1.00		10.00	NR		312.00	surface
	Forest type	0.57	0.25	2.15	1.04	1.20	198.20	surface/passive crown
	Prometheus	0.59	0.31	5.77	0.97	1.16	230.00	surface/passive crown
	Cluster	0.87	0.51	8.58	1.50	1.60	557.60	surface/passive crown
	Standard	0.87	0.71	10.19	1.62	2.04	474.50	surface/passive crown
La Muda	Real	NR		30.00	NR		269.00	surface/active crown
	Forest type	0.85	1.71	25.36	1.32	2.45	91.20	surface/active crown
	Prometheus	3.18	6.44	48.40	4.31	8.67	162.00	surface/active crown
	Cluster	2.03	5.78	39.08	2.79	7.01	212.10	surface/active crown
	Standard	1.87	4.07	50.59	3.03	5.49	250.20	surface/active crown
Costo	Real	NR		2.50	NR		96.51	surface
	Forest type	0.94	0.34	2.06	1.62	1.24	72.00	passive crown spots
	Prometheus	0.79	0.29	2.04	1.40	1.01	79.40	passive crown spots
	Cluster	1.21	0.59	4.97	2.45	2.39	212.40	surface/passive crown
	Standard	1.45	0.83	6.20	3.85	4.00	225.10	surface/passive crown
Grumello	Real	1.00		3.00	NR		4.22	surface
	Forest type	0.44	0.1	0.63	0.59	0.26	2.90	surface
	Prometheus	1.06	0.26	1.67	1.87	0.96	22.00	surface
	Cluster	1.52	0.36	2.31	2.44	1.12	15.00	surface
	Standard	0.96	0.23	1.41	1.10	0.52	8.40	surface
Paladini	Real	NR		5.00	NR		7.66	surface
	Forest type	0.61	0.17	1.17	1.26	0.48	5.20	surface
	Prometheus	1.06	0.35	2.08	1.87	1.34	29.90	surface
	Cluster	1.09	0.53	4.21	1.60	1.04	18.30	passive crown spots
	Standard	0.77	0.25	1.44	0.83	0.43	6.90	surface

Grande simulations were strongly affected by high night-time RH, so the average flame height was always quite low (33-60 cm), but anyway, realistic for the typical fire condition in the area. The 2 m maximum flame heights reported are related to some piled residues that burned during the fire. Standard and Forest type models showed very similar results and a good representation of fire spread and burned area.

Rua fire had complex behaviour, but little information is reported in official statistics. Fire spread as a low-flame surface fire for the most of burned area, but there were some spots of high intensity passive crown fire. All the simulations showed this kind of behaviour.

Average fire spread (0.57-0.81 m min^{-1} and flame height (0.54-0.72 m) were realistic for all the simulations apart from Prometheus models that overestimated fire behaviour.

In San Giusto fire very high flames were registered (2 m average, 4 m maximum), probably because of large and tall formations of *Rubus ulmifolius* L. No simulation was able to simulate such tall flames. Rate of spread was also too low in all the simulations (no simulation reached burned area perimeter).

In Cero fire, Prometheus and Cluster fuel models overestimated maximum flame height (2.33 m and 2.12 m respectively) and rate of spread. The other models showed realistic results.

San Mauro average flame height (1 m) was slightly underestimate by Forest type and Prometheus models (0.57m and 0.59 m respectively) and realistically estimated by all the others. Only Forest type models underestimated maximum flame height. All the simulations reported large areas of continuous passive crown fire in shrubland because of high slope and low crown base height. Crown fire was largely overestimated. In the observed fire there were only passive crown fire spots where some softwood shrubs were burning. Hardwood shrubs could not burn because they were without leaves. Standard and Cluster models strongly overestimated burned area.

In La Muda fire, Forest type models clearly underestimated average flame height (0.85 cm) and rate of spread (1.32 m min^{-1}). The other models looked realistic for the average values but since the fire had very varied behaviour, the average values of flame height and rate of spread were not very representative. We were not able to simulate the explosive behaviour that the fire had in the first 15 minutes. Maximum flame height was realistic in all the simulations (30 m observed, 25-50 m simulated).

In Costo fire, the average and maximum flame heights were realistic in all the simulations. The fire had a very fast spread uphill (10m/min) and slow spread on the flanks so the average rate of spread was realistic in the simulations, but the maximum spread rate was not reached by any simulation. Standard fuel models were the only ones overestimating maximum spread rate (24 m/min). Cluster models correctly estimated the maximum rate (15 m/min). The other models underestimated maximum spread rate.

Grumello fire average (1 m) and maximum (3 m) flame heights were underestimated by Forest type models and realistically simulated by the others. Observed rate of spread was 2 m min^{-1}. Only Cluster models overestimated the rate of spread (2.44 m min^{-1}). The Forest type models strongly underestimated rate of spread (0.59 m min^{-1}).

In Paladini fire the average flame height was realistic in all the simulations (0.61-1.09 m), but just Cluster models showed maximum flame height similar to the real one (5 m observed, 4.21 m simulated). Rate of spread was realistic in all the simulations.

Taking in consideration the global accuracy of every fuel model set, we saw that in LL, in some cases most of the models were able to make a very realistic simulation (i.e. Rua), in other cases no model was able to simulate the fire with high accuracy (i.e. San Giusto, Vendevolo). Total index value (Table 3.6) showed that Forest type and Standard fuel models had the best accuracy. Regarding fire behaviour (Table 3.10), differences among classifications were more evident. Prometheus and Cluster fuel models had strong overestimations or underestimations in more than one case study (Vendevolo, Grande, Rua, San Giusto). Instead, Forest type and Standard simulations were not realistic only in San Giusto fire. As already seen in burned area agreement, Forest type and Standard fire models had very similar results.

In MA case studies Forest type fuel models reached the highest total accuracy index value (SC 3.35, K 3.22), despite the general underestimation of burned area (Table 3.7). Instead as regards fire behaviour (Table 3.9) Forest type fuel models underestimated this in all cases, so they never gave a very realistic simulation. Cluster and Standard fuel models had the best performance in fire behaviour simulation (Tables 3.11).

Table 3.10 – LL – Fire behaviour accuracy (flame height, fire spread, fire type)*

Case study	Forest type	Prometheus	Cluster	Standard
Vendevolo	B	C	C	B
Grande	A	C	C	A
Rua	A	C	A	A
San Giusto	C	C	C	C
Cero	A	B	B	A

*A: realistic; B: quite realistic; C: not realistic

Tab 3.11 - MA – Fire behaviour accuracy (flame height, fire spread, fire type)*

Case study	Forest type	Prometheus	Cluster	Standard
San Mauro	B	B	B	B
La Muda	C	B	B	B
Costo	B	B	A	B
Grumello	C	B	B	A
Paladini	B	B	A	B

*A: realistic; B: quite realistic; C: not realistic

Fire behaviour fuel models calibration

The comparison between fuel model sets gave the Forest type set as the one with the highest accuracy (Tables 3.7, 3.8), but not always the one with the most realistic fire behaviour. We calibrated the Forest type fire behaviour fuel models (Table 2.18) in order to improve their performances in simulating case study fire behaviour (burned area, flame height, rate of spread). In most of the models the main limiting factor was the fuelbed height. In LL models, we increased the softwood plantations fuelbed from 10 cm to 30 cm because using the original data in the San Giusto fire, fire spread and flame height were strongly underestimated. We then decreased the fuelbed height in hop hornbeam from 27 cm to 21 cm because the fire in Mont Cero was burning too fast. In MA, we increased fuelbed height in hop hornbeam from 7 cm to 14 cm to match fire spread in Grumello and La Muda. We then increased the fuelbed from 10 cm to 20 cm in softwood plantations to better simulate La Muda fire. We then increased grassland moisture of extinction from 15 to 20 because otherwise the fire spread in San Mauro almost stopped during the night. Results are shown in Table 3.12.

Table 3.12 – Main parameters of calibrated fire behaviour fuel models

Area	Description	Fuel model code	1H t ha^{-1}	10H t ha^{-1}	100H t ha^{-1}	Live herb t ha^{-1}	Live woody t ha^{-1}	1n area/vol ratio cm^{-1}	Herbs area/vol ratio cm^{-1}	Live woody area/vol ratio cm^{-1}	Fuel Bed Depth m	Dead fuel moisture of ext. %
LL	chestnut	LF1	4.86	7.02	0.88	0.02	2.33	66	59	52	0.20	25
LL	hop hornbeam	LF2	3.88	6.07	0.29	0.09	2.8	66	59	52	0.21	25
LL	shrubland	LF3	2.16	1.98	0.00	0.41	2.94	52	59	46	0.43	20
LL	softwoods	LF4	9.17	2.24	0.00	0.22	0.75	66	59	52	0.30	25
MA	chestnut	MF1	4.29	4.36	0.29	0.10	0.5	66	59	52	0.16	25
MA	hop hornbeam	MF2	6.05	3.72	0.27	0.00	0.31	66	59	52	0.14	25
MA	shrubland	MF3	4.30	2.08	0.00	0.93	0.00	52	59	46	0.15	20
MA	softwoods	MF4	7.46	2.61	0.13	0.32	0.42	66	59	52	0.20	25
MA	grassland	MF5	2.14	0.62	0.00	2.77	0.00	66	59	52	0.18	20

Table 3.13 – LL – Calibrated fire behaviour fuel models accuracy in detail. Global is the value for the whole burned area

							Fire size		**Flame height**		**Rate of spread**	
Case study	**Fuel model**	**SC[1]**	**K[2]**	**A[3] (ha)**	**B[4] (ha)**	**C[5] (ha)**	**observed (ha)**	**simulated (ha)**	**average (m)**	**S.D. (m)**	**average (m min^{-1})**	**S.D. (m min^{-1})**
Vendevolo	LF1	0.49	0.48	3.0	0.1	6.1	9.1	3.1	0.5	0.2	0.6	0.4
Grande	LF1	0.84	0.82	25.1	2.6	7.1	32.1	27.6	0.5	0.1	0.6	0.3
Rua	global	0.72	0.68	44.7	31.7	2.6	47.3	76.4	0.6	0.2	0.6	0.4
	LF1	0.81	0.74	34.5	14.3	1.4	35.9	48.8	0.6	0.2	0.6	0.4
	LF2	0.60	0.58	4.9	5.4	1.1	6.1	10.3	0.4	0.1	0.4	0.1
	LF3	1.00	1.00	2.9	0.0	0.0	2.9	2.9	0.7	0.1	0.9	0.4
	LF4	0.63	0.57	1.1	1.3	0.0	1.1	2.3	0.8	0.2	0.9	0.5
	GR1	0.20	0.19	1.3	10.3	0.0	1.3	11.6	0.3	0.2	0.6	0.3
San Giusto	LF4	0.66	0.64	2.4	2.4	0.0	2.4	4.8	0.9	0.2	1.1	0.5
Cero	global	0.50	0.49	1.4	2.1	0.6	2.0	3.5	0.7	0.2	1.3	0.8
	LF1	0.89	0.88	0.8	0.8	0.1	0.9	0.8	0.7	0.1	1.3	0.9
	LF2	0.00	0.00	1.0	0.0	0.9	0.5	0.9	0.8	0.2	1.0	0.4
	GR2	0.56	0.55	1.0	0.6	1.0	0.6	1.6	0.7	0.2	1.4	0.9

1 Sørensen's coefficient value; 2 Cohen's kappa coefficient value; 3 burned area agreement between observed and modelled fire; 4 simulation overestimation; 5 simulation underestimation

Table 3.14 – MA – Calibrated fire behaviour fuel models accuracy in detail. Global is the value for the whole burned area

							Fire size		Flame height		Rate of spread	
Case study	**Fuel model**	**SC[1]**	**K[2]**	**A[3] (ha)**	**B[4] (ha)**	**C[5] (ha)**	**observed (ha)**	**simulated (ha)**	**average (m)**	**S.D. (m)**	**average (m min^{-1})**	**S.D. (m min^{-1})**
San Mauro	global	0.8	0.7	228.9	46.6	83.2	312.0	265.1	0.7	0.3	1.2	1.2
	MF2	0.7	0.6	105.0	26.3	72.6	177.6	131.3	0.6	0.3	0.7	0.6
	MF3	0.7	0.6	10.0	5.9	2.8	12.8	15.9	0.8	0.3	1.1	0.8
	MF4	0.1	0.1	0.5	5.1	1.6	2.1	5.6	1.4	0.9	1.9	1.4
	MF5	1.0	1.0	81.4	5.6	0.0	2.8	2.9	0.8	0.3	1.6	0.8
	FM5	0.6	0.5	1.6	1.3	1.2	2.8	2.9	0.9	0.3	1.5	0.9
La Muda	global	0.8	0.8	159.9	41.1	46.6	269.0	191.2	2.3	5.1	3.0	6.2
	MF2	0.8	0.8	28.3	1.6	14.3	42.6	29.9	1.7	3.8	2.5	3.9
	MF4	0.8	0.7	113.3	31.4	18.8	132.1	144.7	2.7	5.7	3.3	7.0
	MF5	0.3	0.3	2.4	0.1	9.7	12.1	2.4	1.0	0.8	2.3	2.0
	FM5	0.8	0.8	15.9	3.7	3.6	19.5	19.6	0.9	0.7	2.2	1.6
Costo	global	0.7	0.6	87.7	73.6	8.9	96.5	152.2	1.0	0.4	2.2	2.1
	MF2	0.4	0.3	7.7	24.1	2.3	9.9	31.8	0.6	0.2	0.9	0.7
	MF3	0.6	0.5	13.1	15.4	0.0	13.1	28.4	0.9	0.4	1.4	1.1
	MF5	0.8	0.6	62.2	29.8	5.1	67.3	92.0	1.1	0.4	2.9	2.3
Grumello	MF1	0.5	0.5	4.1	7.4	0.0	4.2	8.7	0.8	0.2	1.4	0.7
Paladini	global	0.6	0.6	7.3	9.3	0.5	7.7	13.7	0.7	0.2	1.1	0.7
	MF1	0.7	0.7	5.4	3.6	0.5	5.9	8.9	0.7	0.2	1.1	0.0
	MF2	0.4	0.4	1.9	5.1	0.0	1.9	6.9	0.7	0.2	1.1	0.0

1 Sørensen's coefficient value; 2 Cohen's kappa coefficient value; 3 burned area agreement between observed and modelled fire; 4 simulation overestimation; 5 simulation underestimation

Table 3.15 – Calibrated fuel models **-** Comparison of main fire parameters (flame height, rate of spread, burned area, fire type).

Area	**Case study**	**Flame Height**			**Rate of Spread**		**Burned area (ha)**	**Fire type**
		average (m)	**S.D. (m)**	**maximum (m)**	**average (m)**	**S.D. (m)**		
LL	Vendevolo	0.49	0.21	0.88	0.55	0.38	3.10	surface
LL	Grande	0.49	0.14	0.99	0.55	0.33	21.90	surface
LL	Rua	0.55	0.20	1.56	0.59	0.37	72.50	passive crown
LL	San Giusto	0.93	0.19	1.43	1.07	0.51	2.90	surface
LL	Cero	0.70	0.19	1.05	1.28	0.79	1.70	passive crown
MA	San Mauro	0.70	0.33	4.84	1.19	1.22	265.10	passive crown
MA	La Muda	2.29	5.09	46.83	2.98	6.16	191.20	active crown
MA	Costo	0.96	0.42	2.90	2.18	2.07	152.20	passive crown
MA	Grumello	0.80	0.2	1.17	1.37	0.68	8.70	surface
MA	Paladini	0.73	0.19	1.29	1.12	0.66	13.70	surface

The accuracy of case study simulations made using Calibrated fuel models are reported in Tables 3.13 and 3.14. The tables report the global simulation accuracy and the details for every fuel model.

In the LL area (Table 3.13) LF1 is the most common fuel and it has a perfect agreement (S=0.80 – 0.89, K=0.74 – 0.88) in the simulations, apart from in the case of Vendevolo (S=0.49, K=0.48), where due to night-time RH, simulations underestimated fire spread. The other fuel models are poorly represented in the simulated fires. LF3 has 100% agreement because it was just in small spots inside the burned area. LF2, LF4 have lower agreement than LF1 but they anyway have a substantial agreement (S=0.60 – 0.66, K=0.57 – 0.64).

In the MA area (Table 3.14), MF1 is found only in Paladini fire where it has substantial agreement (S=0.73, K=0.71); MF2 shows a wide range of agreement between simulations (S=0.53 – 0.78 K=0.51 – 0.76) with the highest agreement in the Alpine fires (La Muda, San Mauro). MF3 is found in two fires, it has perfect agreement in San Mauro (S=0.70, K=0.60) and substantial or low agreement in Costo (S=0.63, K=0.46). The low agreement is due to the suppression that was concentrated in the shrubland at the fire flanks. MF4 performs very well in La Muda fire (S=0.82, K=0.74) and it has no agreement in San Mauro (S=0.13, K=0.11). The lack of agreement in San Mauro is due mainly to suppression. MF5 has a perfect agreement in both the fires where it is found (S=0.78 – 0.97, K=0.56 – 0.95).

The Calibrated fuel models reached at least moderate agreement (K>0.4) in all the case studies and were able to simulate a realistic fire behaviour in all of them, apart from La Muda that, because of its complexity, could not be realistically simulated by any fuel model classification.

Discussion

Evaluation of FARSITE application

Modelling fires accurately is difficult due to a myriad of causes, including spatial heterogeneity in environmental factors and the variable effects of fire suppression over the range of fire sizes (Taylor *et al*. 2013). Additionally, calibration and validation of the fire simulations in general are also made difficult by the multiple sources of error in data, which are confounded by the error of model itself. These sources may include insufficient accuracy in spatial fuels information, the distance between the weather station and the area where the fire occurred, the mapping of fire perimeter or any errors by the user who runs the models (Finney *et al*. 2011).

Despite the use of a fine scale digital elevation model (25 m) and land use map (1:10,000) we had some problems related to map accuracy. The land use map did not report the vertical rocky walls, so FARSITE considered the forest as continuous also where the ground is almost vertical. This resulted in flame height and rate of spread completely out of range. We had also some problems of agreement between fuel map and forest cover map. This resulted in some grassland cells reporting a forest cover higher than zero, and so FARSITE simulated crown fire on those cells.

Another limit in the use of FARSITE is that in MA, the weather inputs are strongly conditioned by local orography (in particular as regards wind) and so the data of ARPAV weather stations are often not very representative of real conditions in the fire area. No meteorological data measured on the fires are available in the case studies because the regional firefighting organization does not provide for their collection during interventions. Last but not least, the evaluation of FARSITE performance is made difficult by the poor information we have about fire behaviour in some of the case studies.

In the La Muda case study, the very steep landscape and the complex orography made the fire simulation particularly complex. The fire was propagated downhill from Monte Cartifai by embers falling down from rocky walls, this kind of propagation cannot be simulated in FARSITE. Using the wind data recorded by the closest weather station (very low wind speed) we were never able to simulate the extreme fire behaviour that happened in the first 15 minutes. To obtain realistic simulations, we had to hypothesize a wind gust of 40 km/h from the south blowing in the first 15 minutes. One of the incident commanders who worked on the fire suggested this hypothesis (Pasa R., personal communication). The possibility of a strong wind gust is also supported by the ignition cause (a tree fell down onto a power line) and from Agordo weather station (6 km from the fire) that reported uphill wind gusts at the same hour. In San Mauro case study, the fire propagation downhill is always much slower than reality because FARSITE does not simulate embers falling down from rocky walls. In Costo case study, the fire crossed the state road six times. In this case, the main difficulty was in evaluating how the road influenced the fire spread. We considered the road not burnable but made it a discontinuous line; in this way the road slowed down the fire without stopping it. Fires burning during the night (Vendevolo, Grande, Rua, San Mauro) are difficult to simulate because fuels easily reached the moisture of extinction during the night and some simulations did not burn at all. An exact local RH measurement is needed in these cases.

For further applications of FARSITE, the collection of weather data on site in real time and a more exhaustive description of fire behaviour in official reports are strongly recommended. Further fuel mapping efforts should be made in mapping forest structure (e.g. by LIDAR technology) in the region to improve fire simulation quality.

Fire accuracy and fuel models selection

Based on the same field data we can have very different fuel models depending on the fuel classification method. The association method based on forest types is very easy to apply and does not give the problem on how to associate the fuel models to existing forest maps, but unfortunately, this method does not consider the high variability found within every forest type (Keane 2013). The fuel models built using this method have average parameters that are rarely able to represent the real local fire behaviour, but, in a wide area, they could simulate a realistic average fire behaviour. In this classification, fuel models can be very similar to each other as reported for chestnut and hop hornbeam in LL. Another problem of this classification is that sixty-nine forest types are reported in Veneto (Del Favero *et al*. 2004) and a statistically significant sampling campaign for all forest types would be too demanding to be realistic in the region. So some approximations are in any case needed. Forest type classification gave quite realistic results in LL study area, apart from softwood plantations (Table 3.6). In MA, this classification always underestimated fire behaviour (Table 3.7).

It was mainly due to the low fuelbed height measured in the field. The sampling season (winter) had an influence on this low fuelbed measure.

The direct classification based on forest structure (Prometheus) creates well differentiated fuel models. An advantage of this method is that fuel models are easy to recognize in the field and can be used in remote sensing applications (Giakoumakis *et al*. 2002). The linkage between this fuel models set and the regional forest map was difficult because the existing maps did not have information on forest structure, so we had to associate to every forest type the fuel model that looked more similar to the average forest structure. In this way, if we used a fuel model with high fuel load there was the risk of overestimating fire behaviour, or vice versa, if we used a low fuel load model the risk was to underestimate fire behaviour. For that reason, Prometheus models did not perform very well in simulating most of the case study fires (Tables 3.6 - 3.11). If we applied the Prometheus model to a forest structure map instead of a forest type map, results would probably be better.

The direct classification method based on cluster analysis showed clear results and allowed us to build eight fuel models well differentiated from each other by fuel load and fire behaviour. Like the Prometheus classifications, information on forest structure is needed, plus information on litter and dead wood fuel load, so the linkage with forest types map becomes even more difficult. It had better performance than Prometheus classification because it avoided the most extreme fuel types (like very light litter or very tall shrubs), but anyway it was not able to correctly simulate all the case studies (Tables 3.6 - 3.11).

The use of Standard fire fuel models gave a good performance in both study areas, probably because we associated Standard fire models to the forest type map mainly based on expected fire behaviour. Since the 53 Standard fire fuel models (Anderson 1982, Scott and Burgan 2005) cover most types of possible fire behaviour, there are good possibilities of finding the right model to represent the average fire behaviour in every forest type. The correct association between Standard fire fuel models and forest type need several tests simulating real fires.

In the abstraction classification method, we modified Forest type fuel models in order to improve simulations quality. In this way a set of calibrated fuel models was built (Table 3.12). Using the Calibrated fire fuel model we had better results in simulating the case study fires than using the other classification methods (Tables 3.13 – 3.15). The calibration process was not anyway able to obtain a perfect simulation in every case study; this is probably due to the highly variable fuel load within forest types (Chapter 2), and the particular fire spread conditions of some case studies. We realized that using this approach, after the modifications, the fuel models became more similar to each other in terms of fire behaviour, so they could be summarized in a lower number of fire fuel models. That is probably because fuels are not always correlated well with vegetation type and the fine-scale variability of fuels within each polygon of similar vegetation is not accurately reflected (Krasnow *et al*. 2009). A limitation of this classification method is that we calibrated fuel models based on a limited number of fires and all these fires occurred in conditions prone to fire, so Calibrated fuel models could overestimate fire behaviour in conditions with low potential for forest fire.

Conclusions

Despite the lack of on-site weather data, FARSITE was able to correctly simulate most of the case studies. The simulation was difficult in the case studies with complex orography, steep terrain and rocky walls (e.g. La Muda, San Mauro). Given that these conditions are very common in the Alps, the use of FARSITE in the area needs a very accurate landscape file and an expert calibration in every simulation. We also had some difficulty in simulating night fires, in this case the main problem was the lack of RH data measured at the fire location.

For further applications of FARSITE, the collection of weather data close to the fire in real time and a more exhaustive description of fire behaviour in official reports are strongly recommended. Further effort should be made in mapping forest structure in the study area (e.g. by LIDAR technology) to improve fire simulation quality.

Classification methods based on forest structure (Prometheus) or on fuel load (Cluster) did not perform very well on the case studies. We think that this happened mainly because we created the fuel map based on the forest type map, so only classified on main species and not considering forest structure or fuel load. Since the same forest type can have very different forest structures, the association between fuel models and forest map often cannot give a good representation of real forest fuels. If we did the same test using a forest structure map, this classification would probably perform much better. Unfortunately, we did not have the possibility to test a forest structure map in this research.

Fuel models built directly associating fuel information to forest types gave a general good performance in simulation accuracy, but, mainly due to the low fuelbed height measured, some of the fuel models underestimated the analyzed fire behaviour outputs (flame height, rate of spread, type of fire). This kind of classification is easy to use but is not able to represent the different fuel conditions that can be found within a forest type.

Standard fire fuel models (Anderson 1982, Scott and Burgan 2005) could be used in the study area with good results, but their correct application needs a study of local forest fuels and testing on several fires as for custom fuel models.

The calibration of Forest type fuel models allowed fuel models efficiency to be improved. The Calibrated fire fuel models were not able to perfectly simulate every fire condition, but differently from the other models, they never had a K value lower than 0.4 and never had completely unrealistic flame height, fire spread and burned area. The calibration process did not allow perfect fire fuel models to be built because the fuel variability was very high and we did not have the possibility to catch the full fuel variability in the landscape, but it allowed fire models to be created that realistically represent an average situation. We suggest that Calibrated fire fuel models could be used for future applications of fire behaviour software in the study area.

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General Conclusions

We showed that in Veneto Region, in the last ten years, the total burned area was very limited (125 ha year^{-1}) and that forest fires generally behaved as surface fires with limited fireline intensity, therefore they appeared to be well under the control of the forest fire-fighting system.

However, an increase in number of large fires is expected in the near future (Valese *et al.* 2014), due to the accumulation of fuel load in Alpine forests, general global warming and the increase of extreme events (Lorz *et al.* 2010, Wastl *et al.* 2012, Elkin *et al.* 2013). The availability of reliable fuel models inputs to be used in fire behaviour prediction systems is therefore an essential requirement for improving the effectiveness of forest fire management in the Eastern Italian Alps.

During the last thirty years, a decrease in the number of fires and total burned area has been recorded, despite the increase in average air temperatures and more extreme weather conditions (Chiaudani 2008). This might be the result of the improvement in both prevention and suppression efficiency (as demonstrated by the change in the distribution of fire sizes in the last 10 years) but other factors could also be involved (e.g. land use changes or social dynamics).

Since 2000, the fire regime in the Veneto Region been in a state of "near-equilibrium" between fire ignitions and fire suppression capacity under not extreme conditions. The fire-fighting system seems to be able to cope with the "average" level of fire risk and, in general, all fires are suppressed within a few hours.

Fuel load in the study areas was similar to what is reported in the literature for similar types of forests. The only exception was the ground dead wood and shrubs in LL that was particularly high, probably due to several widespread phytosanitary problems affecting the Colli Euganei forests. Further investigations would be needed for underhigh foresting the correlation between fuel load and forest health.

Conifer plantations represent a wide category that includes many different species, and, in most cases, they are not properly managed and thus overstocked. Surprisingly, despite the different species, the only significant difference between MA and LL was in the shrubs load.

The type of forest management greatly affects forest fuels: in high forests the main fuels were composed of litter and fine dead wood, while they were shrubs and grass in coppices. Abandoned farmland and pastures had large amounts of herbs and shrubs, and can have a high variability in structure and fuel load.

Fuel size distributions appeared as exponential or logarithmic curves, as reported for other forest parameters (e.g. tree age, tree diameter). Some strong correlations were found between the different classes of ground dead wood. Positive correlations were found between ground dead wood, basal area and dead trees. Instead, herbs and shrubs were negatively correlated with tree diameter, tree height and basal area. In some cases correlations were very similar in the two study areas, in others there were contradictory results between study areas.

The fire simulator software FARSITE was able to correctly predict the evolution of the majority of cases (even if local weather data were not available) . The simulation was difficult in the study cases with more complex orography, steep slopes and rocky walls (e.g. La Muda, San Mauro). Given that these conditions are very common in the Alps, the use of FARSITE in the area would need a very accurate landscape file and an expert user calibration in every simulation.

We showed that simulating night fires is problematic and, in this case, the main limitation was the lack of air relative humidity data measured close to the fire location.

For future applications of FARSITE, the collection of actual weather data close to the fire, and a more exhaustive description of fire behaviour in the official reports would be strongly recommended. Further efforts should be made in mapping forest structure in the study area (e.g. by LIDAR technology) in order to improve fire simulation quality.

Fuel models sets based on forest structure (Prometheus) or on fuel load (Cluster) did not perform very well in the study cases. The main reason for this could be the fact that the fuel map was based on a forest type map, so a map classified only on the basis of main species and not considering forest structure or fuel load. Since the same forest type can have very different forest structures, the association between fuel models and forest map often did not give a good representation of real forest fuels. If the same test was done using a forest structure map, this classification would probably perform much better. Unfortunately, we did not have a forest structure map available in this research.

Fuel models defined by directly associating fuel properties to forest types (Del Favero *et al.* 2004) gave a general good performance in simulation accuracy, but, mainly due to the low fuelbed height measured, some of the fuel models underestimated the analyzed fire behaviour outputs (flame height, rate of spread, type of fire). This type of classification is easy to use but is too rough to account for the variation of fuels within a certain forest.

Standard fire fuel models (Anderson 1982, Scott and Burgan 2005) could also be used in the study area with acceptable results, but for a correct application a study of local forest fuels and the testing on several fires are needed.

The calibration of Forest type fuel models allowed fuel models efficiency to be improved. The Calibrated fire fuel models were not able to perfectly simulate every fire condition, but differently from the other models, they never had a K value lower than 0.4 nor completely unrealistic flame height, fire spread and burned area. The calibration process did not allow perfect fire fuel models to be built, but it allowed fire models to be created that realistically represent an average situation. We suggest that the Calibrated fire fuel models could be used for future applications of fire behaviour software in the study area.

The information on fuel load provided and the custom fuel models obtained in this work do not cover the full vegetation variability found in the Alps but they can test the operative implementation of fire behaviour prediction systems in the most commonly burning Alpine forest types. Further studies on forest fuels are needed in order to extend forest fuel mapping to the whole territory.

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Attachments

Attachment A - Number of fires, burned area, average burned area

Year	LL			MA			Total		
	fires (n.)	burned area (ha)	average burned area (ha)	fires (n.)	burned area (ha)	average burned area (ha)	fires (n.)	burned area (ha)	average burned area (ha)
1981	13	21.4	1.6	212	1511.2	7.1	225	1532.6	8.8
1982	9	30.4	3.4	98	535.1	5.5	107	565.5	8.8
1983	12	99.1	8.3	151	3155.3	20.9	163	3254.3	29.1
1984	10	35.4	3.5	111	1012.0	9.1	121	1047.4	12.7
1985	12	36.8	3.1	82	708.3	8.6	94	745.2	11.7
1986	4	11.0	2.8	94	815.7	8.7	98	826.7	11.4
1987	8	11.9	1.5	119	291.5	2.4	127	303.4	3.9
1988	14	18.0	1.3	138	1584.1	11.5	152	1602.1	12.8
1989	7	3.8	0.5	183	1634.9	8.9	190	1638.6	9.5
1990	37	193.2	5.2	221	2911.2	13.2	258	3104.4	18.4
1991	20	115.0	5.8	89	405.9	4.6	109	520.9	10.3
1992	35	128.1	3.7	131	1089.6	8.3	166	1217.6	12.0
1993	38	165.2	4.3	145	1944.0	13.4	183	2109.1	17.8
1994	16	34.1	2.1	56	132.0	2.4	72	166.2	4.5
1995	0	0.0	0.0	67	760.6	11.4	67	760.6	11.4
1996	8	10.9	1.4	59	302.6	5.1	67	313.5	6.5
1997	11	13.8	1.3	86	1317.9	15.3	97	1331.6	16.6
1998	9	2.3	0.3	96	540.1	5.6	105	542.4	5.9
1999	6	4.0	0.7	38	435.4	11.5	44	439.4	12.1
2000	9	18.9	2.1	57	202.9	3.6	66	221.8	5.7
2001	4	7.3	1.8	20	439.2	22.0	24	446.5	23.8
2002	3	3.5	1.2	59	1452.9	24.6	62	1456.4	25.8
2003	16	101.4	6.3	92	331.9	3.6	108	433.3	9.9
2004	5	4.0	0.8	9	14.0	1.6	14	18.0	2.4

2005	7	2.7	0.4	39	34.0	0.9	46	36.8	1.3
2006	6	38.5	6.4	33	32.3	1.0	39	70.8	7.4
2007	12	6.6	0.6	47	84.2	1.8	59	90.9	2.3
2008	2	5.8	2.9	41	36.9	0.9	43	42.8	3.8
2009	7	9.9	1.4	70	51.8	0.7	77	61.7	2.2
2010	0	0.0	0.0	29	19.8	0.7	29	19.8	0.7
2011	9	7.8	0.9	52	626.9	12.1	61	634.6	12.9
2012	26	22.9	0.9	105	243.8	2.3	131	266.7	3.2
2013	5	10.2	2.0	15	6.0	0.4	20	16.2	2.4
2014	1	0.5	0.5	6	10.1	1.7	7	10.7	2.2
Total	**381**	**1174.3**	**3.1**	**2850**	**24674.2**	**8.7**	**3231**	**25848.5**	**8.0**

Attachment B - Sampling plots localisation (UTM, wgs84)

area	plot	locality	forest type	time zone	X	Y
LL	CC00	Rifugio Monte Rua	chestnut	32t	712818	5022143
LL	CC20	Monte della madonna	chestnut	32t	708142	5026394
LL	CC06	monte grande	chestnut	32t	709257	5026514
LL	CC23	monte grande	chestnut	32t	709134	5026524
LL	CC04	monte grande	chestnut	32t	709891	5026801
LL	CC08	monte grande	chestnut	32t	709054	5026155
LL	CC16	monte grande	chestnut	32t	709595	5027057
LL	CC01	monte Rua	chestnut	32t	712819	5022030
LL	CC14	passo Roverello	chestnut	32t	712127	5021451
LL	CC22	monte perato	chestnut	32t	711856	5019986
LL	CC10	monte vendevolo	chestnut	32t	708795	5020399
LL	CC05	monte vendevolo	chestnut	32t	709077	5020400
LL	CC24	monte vendevolo	chestnut	32t	709338	5020556
LL	CC11	monte ventolone	chestnut	32t	713350	5017869
LL	CC61	monte Grande	chestnut	32t	708707	5026471
LL	OC17	San Biagio	hop hornbeam	32t	711335	5017705
LL	OC12	San Biagio	shrubland	32t	711227	5017683
LL	OC07	M.Calbarina	shrubland	32t	715269	5016997
LL	OC18	M.Calbarina	hop hornbeam	32t	714724	5017087
LL	CC07	M.Calbarina	hop hornbeam	32t	714826	5017173
LL	OC06	monte Cero	hop hornbeam	32t	709786	5014586
LL	OC19	Arquà Petrarca	shrubland	32t	712510	5016983
LL	OC13	monte Cero	shrubland	32t	709815	5014713
LL	OC16	Val S. Giorgio	hop hornbeam	32t	711653	5016165
LL	OC23	Val S. Giorgio	shrubland	32t	711499	5016104
LL	OC22	M. Cero	hop hornbeam	32t	710316	5015401
LL	OC05	Crosara	hop hornbeam	32t	707689	5018910
LL	OC27	Crosara	hop hornbeam	32t	707875	5019001
LL	OC25	Val S. Giorgio	shrubland	32t	711467	5015904
LL	OC20	Val S. Giorgio	hop hornbeam	32t	711464	5015869
LL	OC59	M. Cero	hop hornbeam	32t	709983	5014722
LL	OC42	Val S. Giorgio	hop hornbeam	32t	711830	5016630
LL	PC15	monte calbarine	hop hornbeam	32t	715022	5017113
LL	PC11	monte calbarine	hop hornbeam	32t	714961	5017069
LL	PC03	monte rua	hop hornbeam	32t	712585	5022415
LL	PC10	monte rua	hop hornbeam	32t	712668	5022321
LL	PM11	rosolina	softwoods plantation	33t	289300	5002794
LL	PM12	orto botanico rosolina	softwoods plantation	33t	289783	4997194

LL	PM13	rosolina	softwoods plantation	33t	289397	5002790
LL	PM20	rosolina	softwoods plantation	33t	289491	5002549
LL	PM15	rosolina	softwoods plantation	33t	288961	5001056
LL	PM3	porto viro	softwoods plantation	33t	280631	4990062
LL	PM17	porto viro	softwoods plantation	33t	281296	4991677
LL	PM14	porto viro	softwoods plantation	33t	281417	4991561
LL	PM19	rosolina	softwoods plantation	33t	289675	4996101
LL	PC07	arquà petrarca	softwoods plantation	32t	712484	5016822
LL	PC09	monte cero	hop hornbeam	32t	710023	5014960
LL	PC16	arquà petrarca	softwoods plantation	32t	712578	5016834
LL	PM8	brussa	softwoods plantation	33t	337842	5053624
LL	PM27	brussa	softwoods plantation	33t	338047	5053661
LL	PM29	brussa	softwoods plantation	33t	338958	5053773
LL	PM16	brussa	softwoods plantation	33t	339323	5053779
LL	CC32	forche del diavolo	chestnut	32t	710133	5022704
LL	CC30	pirio	chestnut	32t	711208	5023557
LL	PM9	rosolina	softwoods plantation	33t	289760	4998666
LL	PM2	rosolina	softwoods plantation	33t	289974	4997695
LL	CC43	monte alto	chestnut	32t	715839	5022556
LL	CC17	monte alto	chestnut	32t	716339	5022522
LL	PC21	monte cero	softwoods plantation	32t	709872	5014888
LL	PC2	monte calbarine	shrubland	32t	714929	5016971
LL	PC4	monte calbarine	softwoods plantation	32t	714818	5016902
MA	C38	pianura	chestnut	32t	676517	5065033
MA	C23	pianura	chestnut	32t	676239	5065117
MA	C14	pianura	chestnut	32t	676282	5065163
MA	C25	paladini	chestnut	32t	680815	5066853
MA	C12	paladini	chestnut	32t	680573	5067003
MA	C20	s. chiara	chestnut	32t	694422	5069532
MA	C22	combai	chestnut	33t	271404	5089628
MA	C15	combai	chestnut	33t	271758	5089628
MA	C09	combai	chestnut	33t	271860	5089701
MA	C19	combai	chestnut	33t	271780	5089953
MA	C06	sonego	chestnut	33t	293954	5100914
MA	O10	il pavagno	hop hornbeam	32t	653623	5049562
MA	C11	ceredo	hop hornbeam	32t	653854	5053208
MA	C01	ceredo	hop hornbeam	32t	653563	5053424
MA	C05	summano	hop hornbeam	32t	688209	5069347
MA	O14	costo	hop hornbeam	32t	689535	5074413
MA	A11	costo	hop hornbeam	32t	688672	5074597
MA	A02	costo	hop hornbeam	32t	688603	5074609
MA	O13	solferino	hop hornbeam	32t	724994	5107070

MA	O11	solferino	hop hornbeam	32t	724516	5107083
MA	O22	sonego	hop hornbeam	33t	293871	5100747
MA	O08	croda rossa	hop hornbeam	33t	290299	5101053
MA	A10	calcari	shrubland	32t	658515	5044528
MA	A17	summano	shrubland	32t	685533	5068360
MA	A03	summano	shrubland	32t	685643	5068535
MA	A24	costo	shrubland	32t	688597	5074449
MA	A22	costo	shrubland	32t	688555	5074678
MA	A18	monte caina	shrubland	32t	708850	5076494
MA	A07	monte caina	shrubland	32t	708955	5076563
MA	A25	monte caina	shrubland	32t	708971	5076587
MA	A15	lepre	shrubland	32t	710833	5083350
MA	A01	stoccaredo	shrubland	32t	702459	5084363
MA	O24	val san martino	shrubland	32t	723473	5107665
MA	O21	val san martino	shrubland	32t	723287	5107956
MA	O09	sonego	shrubland	33t	293897	5100493
MA	O16	croda rossa	shrubland	33t	290531	5101037
MA	P07	M. nuvola	softwood plantation	32t	654184	5050039
MA	P14	foza	softwood plantation	32t	704034	5086721
MA	P18	foza	softwood plantation	32t	703950	5086730
MA	P05	solferino	softwood plantation	32t	724735	5106853
MA	P16	solferino	softwood plantation	32t	724591	5106973
MA	P03	solferino	softwood plantation	32t	725142	5107078
MA	S29	la muda	softwood plantation	33t	276868	5125363
MA	S04	la muda	softwood plantation	33t	276725	5125409
MA	S19	la muda	softwood plantation	33t	276822	5125434
MA	S05	la muda	softwood plantation	33t	276095	5125726