Fire Spread Modelling in Majella National Park, Italy

Upenyu Naume Nyatondo
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by

Upenyu Naume Nyatondo

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Thesis Assessment Board

Chairman:	Dr. Ir. C.A.J.M. (Kees) de Bie
External examiner:	Prof. Katarzyna Dabrowska
First supervisor:	Ms. Ir. Louise van Leeuwen
Second supervisor:	Dr. Hein van Gils
Course coordinator:	M.Sc. A. (Andre) Kooiman

ITC

UNIVERSITY OF TWENTE.

FACULTY OF GEO-INFORMATION SCIENCE AND EARTH OBSERVATION

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Abstract

Fire behaviour modelling has not been done in montane conditions. This study was aimed at testing the applicability of FARSITE (Fire Area Simulator) simulation model in montane conditions using a fire event of July 2007 in Majella National Park, Italy. The following questions were raised: (1) Does the simulated fire extent approximate the observed fire scar by at least 75%? (2) How is simulated fireline intensity distributed within the simulated fire scar? (3) Can fire modelling be useful in identifying the ignition points? (4) Does the incorporation of spatially varying wind information improve the accuracy of the accuracy of the model? The land cover types within the area were mapped by supervised classification of ALOS satellite imagery into grass, beech, pine forest, mixed broadleaf-deciduous forest and bare area. The fire behaviour simulation in FARSITE model was based on fuel, topography and weather conditions. The model also utilizes an ignition point for the fire. The fuel information was provided in the form of fuel models describing the vegetation physical properties in the study area. Topography data (elevation, slope, aspect) was acquired from a digital elevation model. Weather data (temperature, humidity, rainfall, wind speed, wind direction) was acquired from ‘‘Punta dell’est’’ Roccacaramanico weather station. The simulation in FARSITE using this information resulted in fire perimeter and fireline intensity maps. The effect of incorporating spatially uniform and spatially varying wind data was tested. For each scenario the effect of adjusting the rate of fire spread was tested on the fuel models for pine and grass. The spatial variation of wind was simulated in the WindNinja model to include the effect of terrain on wind behaviour. The simulations were compared with the mapped fire scar (observed fire scar). The percentage agreement between the simulated and observed fire scars was calculated. Sorensen’s and Kappa Coefficients were used as measures of the accuracy of the simulation. Simulations including spatially uniform wind underestimated the extent of the fire spread. Incorporation of the spatially varying wind increased the similarity between the simulated and the observed fire scars. Fuel model adjustment also increased the similarity between the simulated and observed fire scars. Fireline intensity was highest in the pine forest whilst in the grass, beech and mixed forest the intensity was low. The comparison between simulation using a hypothetical and observed ignition points indicates that the model is useful in identifying ignition points. The study results indicate that FARSITE fire model can only be applied well in montane conditions if the spatial variation of wind is included in the simulation.

Key words- FARSITE, Fire spread behaviour, Wind Ninja

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List of abbreviations

ALOS	Advanced Land Observing Satellite
DEM	Digital elevation model
FARSITE	Fire Area Simulator
FLAMMAP	Fire Mapping and Analysis System
MODIS	Moderate Resolution Imaging Spectroradiometer
BEHAVE	Fire Behaviour Prediction and Fuel Modelling System
USDA	United States Department of Agriculture

1. Introduction

1.1. Background

1.1.1. Forests and Fire

Although fires are responsible for shaping most of the ecosystems, they can be destructive both to vegetation and human life (Boschetti et al., 2008, Carmel et al., 2009). Fires have a major role in the global carbon cycle (Lu et al., 2006, Merino-de-Miguel et al., 2010) and are a primary disturbance in most forest ecosystems (Fraser and Li, 2002). These fires influence the ecosystem structure and processes by reallocating carbon among different carbon pools (Lu et al., 2006, Lu et al., 2005). Fire results in direct release of carbon-containing traces into the atmosphere (Lu et al., 2006) which significantly contributes to variations in the atmosphere concentrations (Wotawa and Trainer, 2000). The global climate change is influenced by these fire induced gases especially carbon dioxide and methane (Swetnam, 1993). These and other various effects of fire have led to the modelling efforts by fire scientists in order to understand the behaviour of fire propagation in various land cover types (Mbow et al., 2004). This is important in assisting fire management.

1.1.2. Environmental conditions and fire

The ignition and burning of fire requires three major factors which include oxygen, heat and fuel. Fuel is the material that burns and is characterised by its type, chemical composition and moisture content (Pyne et al., 1996). There should be enough heat to make the fuel burn and oxygen should be sufficient to make the process of burning successful. These factors form what is well known as the fire triangle. In the presence of appropriate fuel, enough oxygen and adequate heat, burning will occur and the absence of one of these factors stops the fire (Pyne et al., 1996).

One of the most important aspects of wildfires is their behaviour. The success of suppression activities depends on how well fire managers can understand and predict the behaviour of a fire. The understanding of fire behaviour is also important for effective fire prevention measures such as location of fire breaks and the identification of fire risk areas (Mbow et al., 2004). Fire behaviour refers to the magnitude, direction and intensity of a fire spread. Fire spread is known as a series of ignitions where heat from the fire causes the fuel temperature to rise to ignition temperature (Rothermel, 1983). The behaviour of fire depends highly on the interaction of environmental conditions, which are mainly vegetation (fuel), topography and weather (Salis, 2008). The importance of these factors is highlighted in Chapter 4.

1.1.3. Fire Behaviour Modelling

Advances in computer software technology have allowed for the development of fire behaviour simulation models. These are aimed at predicting the spread rate and direction and intensity of fire. Fire behaviour simulations provide near real-time support to fire suppression tactics, improves logistics decision making and thereby improve the safety of firefighters (Andrews and Queen, 2001, Carmel et al., 2009). Fire risk areas and possible locations for fire breaks can be identified through fire behavior simulations. The high risk climatic conditions can also be determined through fire behavior simulations. Fire models help to assess the way that the fuel may burn (Andrews and Queen, 2001).

Fire behaviour prediction systems such as BEHAVE (Andrews and Queen, 2001, Andrews, 1986, Andrews et al., 2007) fire modelling system , FlamMap (Stratton, 2004) fire mapping and analysis system and FARSITE (Finney, 1998) fire area simulator have been developed for fire behaviour prediction BEHAVE fire model does not include the spatial variation in landscape in its fire behaviour simulations. FlamMap uses spatial information on topography and fuels to calculate fire behaviour characteristics at one instant (Stratton, 2004), without temporal variation. This does not reflect reality because fire is a continuous process. FARSITE's simulations incorporate the variations in fire behaviour both temporally and spatially and simulate the fire spread process. FARSITE therefore represents reality more than the other fire models.

FARSITE model is based on mathematical models of fire spread behaviour (Rothermel and Rinehart, 1983, Rothermel, 1972). Whilst BEHAVE only simulates surface fire, FARSITE has been modified to simulate both surface and crown fire. FARSITE has been intensively used to simulate past, active and potential fires (Arca et al., 2006, Arca et al., 2005, Molina-Terrén et al., 2006, Andrews et al., 2007, Arca et al., 2007, Arroyo et al., 2008, Butler et al., 2006a, Carmel et al., 2009, Dimitrakopoulos, 2002, Dwomoh, 2009, Forthofer and Butler, 2007, Halada et al., 2006, Hargrove et al., 2000, Mbow et al., 2004, Miller and Yool, 2002, Mutlu et al., 2008, Ryu et al., 2007, Stephens, 1998).

Simulation of past fires is important for comparison of simulated fires with the known fire growth and adjusting/validating the model for a given landscape. The simulation of active fires helps in decision support for fire suppression and the computation-based control under given conditions. The simulation of potential fires, however, is for prevention purposes where the possibility of the suppression and prevention of the potential fire is analyzed (Halada et al., 2006). It is therefore important to simulate historical fires in order to learn to forecast the behaviour of future fire events (Molina-Terrén et al., 2006, Finney, 1998). The simulation of fire intensity and rate of fire spread could assist in the planning of fire suppression activities and also offer information for the safety of the fire-fighters. Simulation of fires is also important considering that future climate estimates predict an increase in temperature in South East Europe which may lead to increase in the occurrence of fire events (IPCC., 2001, Scholze et al., 2006).

1.2. Problem Definition and Justification

Although several studies (Arca et al., 2006, Arca et al., 2005, Majlingová and Vida, 2008, Molina-Terrén et al., 2006, Salis, 2008) have been done on the simulation of fire events in Europe using fire models, no study has been done in montane areas. Most of the studies were done in Mediterranean conditions (Arca et al., 2006, Arca et al., 2005, Arroyo et al., 2008, Halada et al., 2006, Arca et al., 2007, Dimitrakopoulos, 2002, Salis, 2008, Miller and Yool, 2002). The Mediterranean conditions are considered to be highly sensitive to fires due to long, dry summers with high temperatures which reduce the fuel moisture content (Carmel et al., 2009, Salis, 2008, Arca et al., 2007). Studies on the simulation of fires using fire spread models in montane conditions may have been limited because the conditions are considered to be unsusceptible to fires. The montane areas are characterized by high altitude, snowy winters, cooler summers, absence of summer drought and high average rainfall (Braun, 1980, Kitayama, 1995, van Gils et al., 2010, van Gils et al., 2008, Vitousek, 1998). Fire is likely to behave differently in montane areas as compared to Mediterranean areas due to differences in the fire determinants (vegetation, weather, topography). Vegetation and hence fuel characteristics in montane areas is different from other areas. Wind behaviour, for example, is different at higher altitude such as montane areas compared to lower altitude area. Fire models may therefore also behave differently in these different conditions. It is important to note that rare montane fire events such as the one which occurred in Majella National Park can occur and therefore there is need to study the behaviour of such fires. It is important to map fire intensity using fire models in order to determine ways of controlling fires by fire managers (Perry, 1998). The simulation of fire behaviour requires the location of fire ignition points. This is helpful in cases where the location of ignition point/s is not known or unclear. Multiple simulations can be performed keeping other factors constant and varying the ignition point until the shapes of the simulated and observed fire scars are closely similar. FARSITE fire model can be used to identify possible ignitions (www.fs.fed.us/psw/topics/fire_science/craft/craft/Resources/Fire_models_tools.htm #Farsite). The identification of areas which are highly sensitive to fire is another important ability of fire modelling (Carmel et al., 2009). Identifying such areas in the montane conditions could improve the management of forests to reduce fire occurrence.

1.3. Research Objectives

In view of the problem highlighted, the study addressed objectives, answered questions and proved the following assumptions.

1.3.1. General Objective

The general objective of this study is to test the applicability of fire spread modelling in montane areas

1.3.2. Specific Objectives

The specific objectives of the research were:

- To simulate the extent of fire spread area under montane conditions
- To evaluate the effect of incorporating spatial variation in wind speed and direction on the approximation of fire area simulation
- To map the spatial distribution of fireline intensity of the fire event in Majella National Park
- To evaluate the potential of fire spread modelling in the identification of possible ignition points

1.4. Research Questions

Based on the above objectives, the following research questions were answered:

- Does the simulated fire extent approximate the observed fire scar by at least 75%?

- Does the incorporation of spatially varying wind information improve the accuracy of the accuracy of the model?
- How is simulated fireline intensity distributed within the simulated fire scar?
- Can fire modelling be useful in identifying the ignition points?

1.5. Assumptions

The following research assumptions were tested in this study:

- The simulated fire extent approximates the observed fire scar by at least 75%
- The incorporation of spatially varying wind data improves the similarity in shape and size between the observed fire area simulation

2. Concepts and Definitions

2.1. Definition of Terms

The definitions of the terms that have been used in this study have been listed in

Table 2-1: The definition of terms

Term	**Definition**
Rate of fire Spread m /sec	Speed at which fire travels through the fuel.
Fire line intensity (kW/m)	Heat energy released per unit time.
Heat per area –(KJ/ m^2)	The amount of heat energy released per area within the flaming front of surface fuel. It is independent of wind, slope or direction of fire spread and depends only on the fine fuels affecting fire spread.
Fuel bed depth (cm)	The depth of the surface fuel. The calculation of fire spread by the Rothermel's model is highly sensitive to the changes in fuel bed depth.
Dead fuel Moisture of extinction (%)	The amount of fuel moisture in dead fuel above which fire spread is not possible.
Live fuel Moisture of extinction (%)	The amount of fuel moisture above which the live fuel becomes a heat sink. The live fuel contributes to the surface fire spread when the fuel moisture is below the live fuel moisture of extinction.
Fuel Heat Content (kJ/kg)	The amount of heat energy contained within a unit of fuels. In standard fuel models the heat content is 18.622kJ/kg.
Fuel loading (tons / ha)	The total amount of live and dead fuel. The higher the fuel load the higher the amount of heat produced during a fire. The fuel load and depth determine fire ignition, rate of spread and intensity.
Live Herbaceous Fuel Load (tons / ha)	The weight of living grasses and forbs per unit area. This includes both annual and perennial fuels.
Live Woody Fuel Load (tons / ha)	The weight of foliage and very fine stems of living shrubs per unit area.
1-hr fuel load (tons / ha)	The weight of fine fuels such as needles, leaves, cured herbaceous plants and fine dead stems of plants per unit area. The fine fuels have a diameter below 0.64cm.
10-hr fuel load (tons / ha)	The weight of fuels of diameter (0.64-2.54cm) per unit area.
100-hr fuel load (tons / ha)	The weight per unit area of dead fuels of diameter 2.54 to 7.62cm. It is assumed that fuels with larger diameter than this category do not contribute to the rate of fire spread.
Heat yield	The total heat minus energy required to vaporize moisture in fuels

Source: (Anderson, 1982, Andrews, 2009, Miller and Yool, 2002, Scott and Burgan, 2005)

2.2. Fire models

2.2.1. Description

Fire models have been developed to simulate fire behaviour and its dependence on fuel, weather and topography (Forghani et al., 2007). Fire behaviour predictions are aimed at providing near real time support for fire suppression and logistics decision making thereby improving communication among decision makers (Andrews and Queen, 2001).

Most fire models are based on the Rothermel's fire propagation model (Andrews and Queen, 2001, Rothermel, 1972). Rothermel's fire propagation model provides a good approximation of fire spread as described in Equation 1.

$$R_0 = \frac{I_r \xi (1 + \phi_w + \phi_s)}{\rho_b \in Q_{ig}}$$

Equation 1: Rothermel's fire spread model

Where,
R_0 = the forward rate of spread of the flaming front (m min^{-1}),
I_r = the reaction intensity (kJ m^{-2} min^{-1}),
ξ =the propagation flux ratio (dimensionless),
ϕ_w =the wind coefficient (dimensionless)
ϕ_s = the slope factor (dimensionless)
ρ_b = the fuel bed bulk density (kg m^{-3})
ε = the effective heating number (dimensionless)
Q_{ig} = the heat of pre-ignition of fuel (kJ kg^{-1}) (energy required for ignition)
(Mbow et al., 2004, Rothermel, 1972, Perry, 1998)

Equation 1 shows that the propagation of fire through biomass is dependent on the amount of heat that is transferred to adjacent fuel which is not yet ignited (Mbow et al., 2004, Rothermel, 1972). The numerator represents the amount of energy that reaches the non-ignited fuel whilst the denominator represents the amount of heat that is required by the fuel to reach ignition temperature (Mbow et al., 2004, Rothermel, 1972, Perry, 1998). The Rothermel (1972) equation assumes that weather, topography and fuel at an elapsed time are constant and uniform (Andrews, 2009). Topography (slope, aspect, elevation) directly affects fire propagation whilst indirectly affecting fuel moisture status (Mbow et al., 2004). It is important therefore to clearly define topography and wind in fire models because they introduce variation in the fire propagation.

The Byram's fireline intensity (Byram, 1959), described in Equation 2, is another important equation which works together with the Rothermel's model in fire models.

$$I = HWR$$

Equation 2: Byram's fireline intensity equation

Where:
I = fireline intensity (kW. M^{-1})
H = heat yield of the fuel (J. g^{-1})
W = mass of the fuel consumed ($g.m^{-2}$)
R = rate of fire spread (m sec^{-1}) (Byram, 1959)

Equation 2 shows that the fireline intensity is influenced by heat yield, fuel availability and the rate of fire spread (Perry, 1998).

Models such as BEHAVE, numeric model (Andrews et al., 2007, Andrews, 1986) and FARSITE (Finney, 1998) are decision support systems. FARSITE (Finney, 1998) is a fire growth simulating model, which utilizes the spatial information on fuels, topography and weather. It incorporates existing models for surface fire (Rothermel, 1972), spotting (Albini, 1976), crown fire (Wagner, 1993) and fuel moisture (Nelson, 2000) in its fire behaviour simulations. This therefore means that FARSITE is a comprehensive fire model and incorporates the functions of the previous models. Unlike the BEHAVE (Andrews, 1986) which varies only temporally, FARSITE modelling varies both spatially and temporally and produce outputs such as fireline intensity and burned area (Arca et al., 2007). The simulation of fire in FARSITE is based on the Huygens' technique (Finney, 1998, Stratton, 2004, Anderson, 1982) which assumes that the surface fire front expands as elliptical wave propagations in two dimensions (Finney, 2004).

The development of FARSITE fire model was originally for simulation of prescribed fires in United States national parks and wilderness areas (Arca et al., 2007). Prescribed fires are usually set on purpose for fuel management purposes. Some of the uses of prescribed burning include improving forage for grazing, perpetuating fire dependant species, hazardous fuel reduction and for disease control

(Wade et al., 2000). The validation of the model was done using fires that have occurred in such areas. In other areas, mainly Europe and Australia both the Rothermel's and the FARSITE models have been validated (Miller and Yool, 2002, Dimitrakopoulos, 2002). This makes FARSITE a well proven fire model and hence applicable in this study.

Arca et al (2007) evaluated the capabilities of FARSITE in accurately simulating fire spread behavior in Mediterranean conditions. They also analyzed the effect of fuel models, weather conditions and topography on the simulations. The incorporation of custom fuel models resulted in more realistic values of rate of spread. They concluded that the accuracy of wind data and fuel models is essential for realistic fire modelling in FARSITE. Mbow et al (2004) applied fire behaviour modelling to validate fire risk maps in savannah conditions in Senegal (West Africa) using FARSITE together with LANDSAT-ETM data. They observed high consistency between simulated and observed fire scars.

2.3. Fuels

2.3.1. Description of fuel parameters

For any fire to occur there should be the fuel to ignite. The vegetation characteristics determine the fuel conditions in a given area. Fuels are described in terms of the physical characteristics of their live and dead biomass. These characteristics contribute to the spread, intensity and severity of wild land fire (Andrews and Queen, 2001). Such physical characteristics include loading (weight per unit area), size (particle diameter), shape, bulk density (weight per unit volume) and arrangement (Arroyo et al., 2008). Large particles, for example, require more heat to ignite and burn the particle. Less energy is required to ignite and combust small fuel particles. In dead fuels the particle size also relates to the rate at which fuel moisture content changes. The smaller the particle size the faster the loss of moisture. The size classes (e.g. 1 hr fuels, 10 hr fuels, 100 hr fuels) of the fuels are also referred to as time lag classes which burn differently.

The surface area-to-volume (SAV) ratio is also related to particle size. Higher surface area provides more surface area for heat oxidation and combustion. The fine fuels such as grasses, ferns and conifers also dry out and ignite more rapidly than coarse fuels. Hardwood litter can burn under dry conditions but they are less flammable than grasses and conifers because of lower SAV. Most oaks, for example, have higher SAV than deciduous hardwoods (Papió and Trabaud, 1990, LaCroix et al., 2006). The description of the fuel parameters is utilized in fire modelling by incorporation them in fuel models.

Weather and topography influence the fuel conditions. The geometry of the sun angle and terrain for a specific time, date and latitude, attenuate the sunlight. The heating and drying due to solar radiation also determine the moisture in the fuel. Forest canopy cover may reduce the solar irradiance and hence determine the fuel moisture conditions. It is therefore essential to characterise the vegetation conditions in order to have representative fuel conditions for fire modelling.

2.3.2. Application of fire models

Fire models have been developed mainly for the prediction of fire growth behaviour. Fire models like BEHAVE (Andrews, 2009) have been applied to assess the effect of changing the conditions of fuels (fuel moisture, wind) on fire behaviour. The fire models have also been applied in the assessment of fire risk areas (Mbow et al., 2004, Carmel et al., 2009). Organizations such as USDA Forest Service and the USA national parks have extensively used fire models such as FARSITE in the projections of wild fires. The realistic simulation of fire behavior by fire models depends on consistency and accuracy of the weather data and also on the accuracy of the fuel models and other parameters (Arca et al., 2007, Mbow et al., 2004).

2.4. Wind Behaviour

2.4.1. Wind Modelling

The spatial variation of wind data that is used in fire models is a major source of uncertainty in fire behaviour predictions (Forthofer and Butler, 2007, Forthofer et al., 2009, Forthofer, 2007). Wind is one of the environmental variables which greatly influence the spread and intensity of wildland fires (Rothermel, 1972). Its behaviour usually fluctuates on relatively small temporal and spatial scales. Wind information is mostly acquired from weather forecast and/or weather observations at specific location, usually not near the fire location. Such wind information lacks spatial description (Lopes, 2003). The lack of detailed information on wind speed and direction for use in fire behaviour simulations is usually a major source of uncertainty in fire behaviour predictions (Butler et al., 2006a).

Landscape characteristics such as mountainsides, valleys, ridges as well as the fire itself tend to influence the speed and direction of wind flows. Such terrain usually produces complicated local wind patterns which make fire behaviour modelling difficult. Fire behavior analysts have traditionally relied on broad-scale, uniform wind speed and direction (from weather station) which do not describe the localized terrain effects on wind (Forthofer and Butler, 2007, Forthofer, 2007). The modelling of wind behaviour in such terrain has been shown to improve the prediction of fire perimeters by fire models (Forthofer et al., 2009, Forthofer, 2007, Butler et al., 2006a, Butler et al., 2006b, Forthofer and Butler, 2007, Forghani et al., 2007).

Wind modelling involves the simulation of the influence of terrain on wind flows (Butler et al., 2006a). The spatially varying wind flow which occurs due to terrain modification has the ability to improve the simulation of fire spread (Forthofer and Butler, 2007, Forthofer et al., 2009, Forthofer, 2007). The information also helps in identification of locations where fire spotting may occur. This spatially varying wind data is also referred to as gridded wind data.

At least three microscale wind models have recently been developed to improve fire behaviour simulation. These include WindStation (Lopes, 2003), WindWizard (Forthofer, 2007) and WindNinja (Forthofer, 2007). The evaluation of the accuracy of wind simulation has indicated an agreement between simulated gridded winds and measured wind averages from wind speed/direction meters in the field (Forthofer and Butler, 2007, Forthofer, 2007, Butler et al., 2006b).

FARSITE fire spread model (Finney, 1998, Finney, 2004) incorporates wind in fire modelling and by default assumes that wind varies temporally but not spatially over the modelling domain (Rothermel, 1972). This is a poor description of the wind field, especially in terrain with heterogeneous topography. It is however possible to incorporate the modelled spatial varying wind data into FARSITE fire model. The model however does not incorporate the effect of the fire on the wind behaviour. In areas such as Majella National Park the spatial variability of wind is a major factor affecting fire behaviour.

3. Materials and Methods

3.1. Study area

3.1.1. Criteria for selection of study area

The study was undertaken in Majella National Park, which is one of the largest National Parks in Europe. The park covers an area of about 740km^2 (van Gils et al., 2008). The park is characterized by hilly topography as illustrated in Figure 3-1.

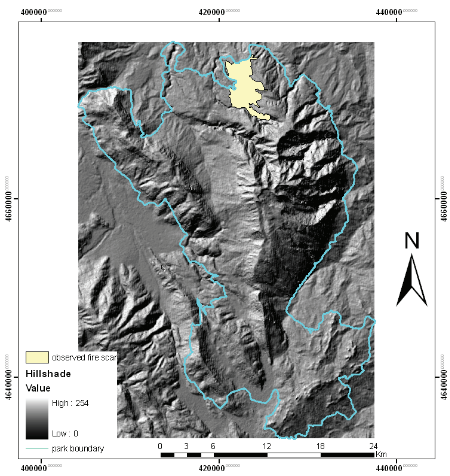


Figure 3-1: The illustration of the topography in Majella National Park

The area was selected for study due to the availability of published information on the fire event, the fire scar. The hilly topography and topographic heterogeneity of the area as shown in Figure 3-1 allowed for testing the effect of incorporating spatial variation in wind in fire modelling. The simulation of the behaviour of fire spread is therefore important in order to develop strategies to minimize the extent of fires (Scott and Burgan, 2005) and for the planning of suppression activities. The availability of a burned area map of the 2007 fire for the accuracy assessment of the model simulation also makes the study area suitable for the study.

3.1.2. Characteristics of the study area

The study area includes a fire scar and its surroundings within 2km. This area is found within the northern part of Majella National Park in Abruzzi, Italy (latitude $41^{0}52'$ to $42^{0}14'$ N, longitude $13^{0}50'$ to $13^{0}14'$ E). The fire scar (17.2km^2) was GPS-surveyed by the park management in August 2007 (van Gils et al., 2010) and encompassed the municipalities of Roccamorice and Lettomanopello in the province of Pescara. The altitude within the fire scar ranges from 600 to 1400m and characterized by forb-and-grass covered abandoned farmlands as well as the beech and pine forests. Figure 3-2 shows the study area including a 2km buffer created around the fire scar to cover an area of 79.7 km^2. A buffer of 2km was suggested based on the feasibility of data collection during the given field work period and to allow more area for the simulation.

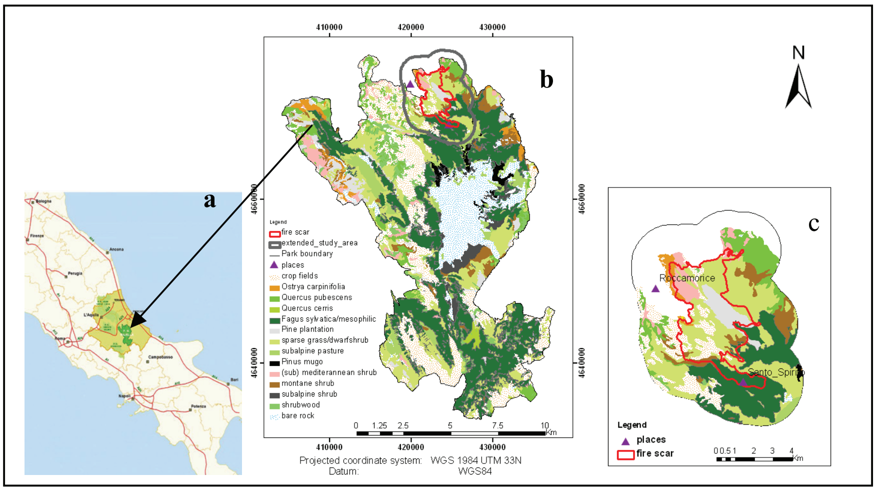


Figure 3-2: A map showing a) the location of Majella National Park within Abruzzi region in Italy b) the location of the study area within the park and c) the extended study area

The burnt beech and the pine forests lie at the lower fringe of the montane belt (900-1300m) (van Gils et al., 2010). The sub-Mediterranean pubescent oak (*Quercus pubescens Wild*) and hop-hornbeam (*Ostrya carpinifolia Scop*) forests occur further down slope, at an elevation of about 900-500m. In this study the pubescent oak and the hop-hornbeam have been lumped into broadleaf-deciduous forest which is further referred to as 'mixed forest'. Between the burnt beech and pine forests lies the abandoned farmland which was intensively used as summer pastures prior to its abandonment around the mid-20th century (van Gils et al., 2010, van Gils et al., 2008). The presence of cone-shaped, dry stone shepherd shelters ('tholos') testifies that the land was used as summer pastures. The distribution of the vegetation belts within the study area is shown in Figure 3-1. The land is currently either grazed at low intensity or ungrazed (Bemigisha, 2008). The forests in the study area lie in the Protection Zone B (www.parcomajella.it, 2009), where there is routine removal of deadwood from the forest floor (van Gils et al., 2008, van Gils et al., 2010). This implies that the fuel load in the forest is lower than in other unmanaged beech forests.

3.1.3. Climatic conditions

The study area is located within the lower, warm Apennine beech belt (Piovesan et al., 2005). The belt is characterized as 'montane' due to high relief (930-1600m above sea level) (van Gils et al., 2008), snowy winters, cooler summers, absence of summer drought and high rainfall (Braun, 1980, Kitayama, 1995, van Gils et al., 2010). Climatic data from Passo Lanciano weather station (1470m), which lies just above the eastern end of the study area indicates that the precipitation curve is usually above the temperature curve. This is shown in Figure 3-3 and illustrates the absence of summer drought.

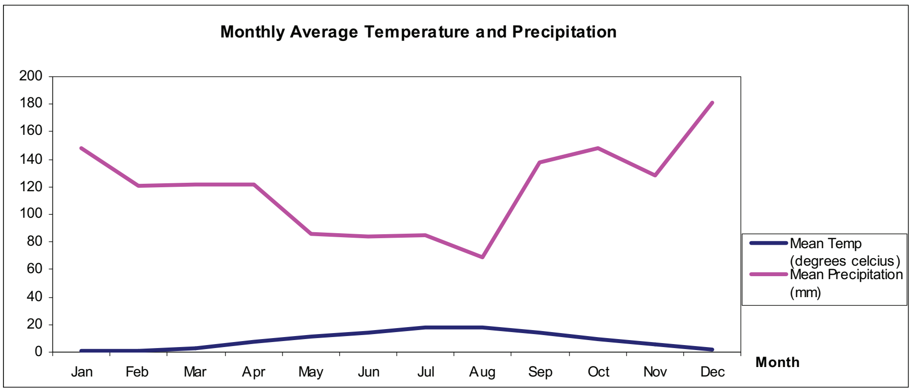


Figure 3-3: The average monthly temperature and precipitation
Source: (Passo Lanciano weather station)

3.2. Materials

3.2.1. Data

The data which was used in this study and the sources are listed in Table 3-1.

Table 3-1.The list of data collected in the research

Data	Source
30 minute weather data (Temperature, rainfall, humidity, wind direction, wind speed)	‘‘Punta dill’s’’ Roccacaramanico meteorological station
Topography data (Elevation, aspect, slope)	Digital elevation model from Majella National Park
Canopy cover	Field estimation
Land cover map	Supervised classification of ALOS imagery
Fuel models	Selection from the standard fuel models by Scott and Burgan (2005)
Fire scar map	GPS mapping by the National Park management
Roads	Digitized from aerial photograph
Possible ignition points	Park management, Ground observation, MODIS active fire data

Source: Author

3.3. Methods

3.3.1. Flowchart of the method

The flowchart of the method used in this study is shown in Figure 3-4.

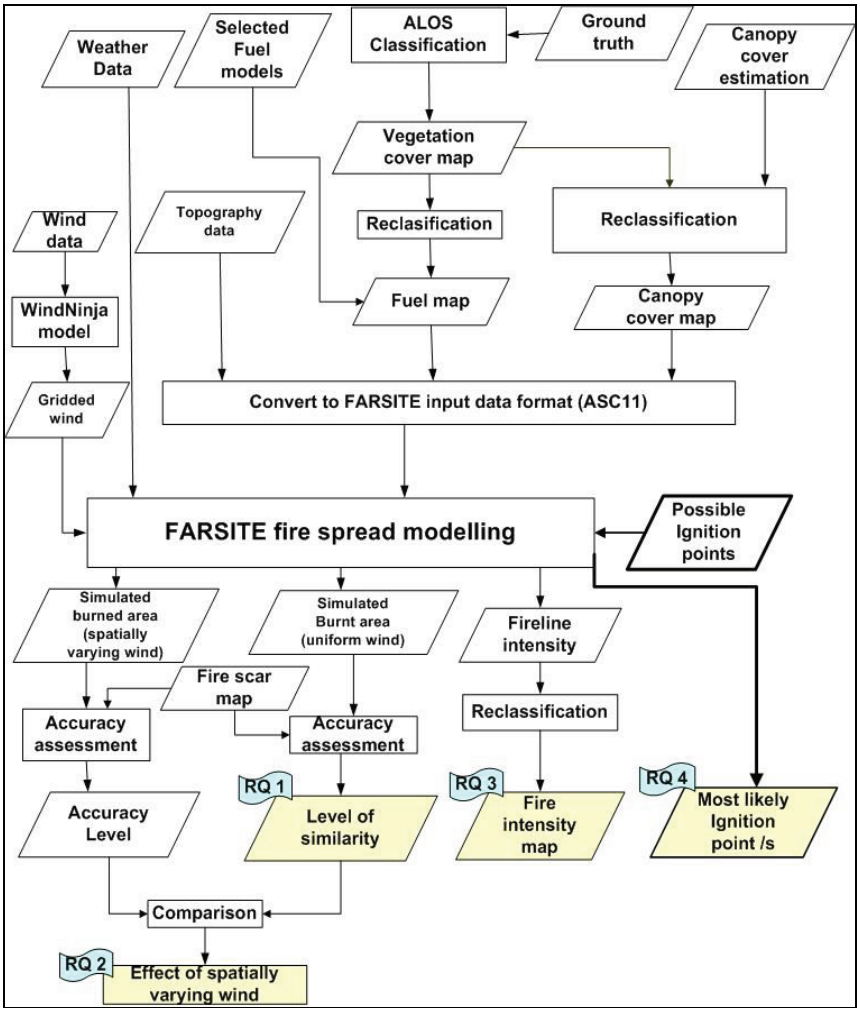


Figure 3-4: The flowchart of the processes undertaken in the study

The flowchart in Figure 3-4 shows the outline of the methods followed in the study starting from the preparation of the model inputs. The expected outputs to answer the proposed research questions are highlighted. The fire simulation was divided into two parts where spatially uniform and varying wind data were incorporated respectively. The comparison of the results from the two approaches was then done.

3.3.2. Preparation of Model Input data

Simulation of the fire event was done in FARSITE (Fire Area Simulator) (Finney, 1998, Finney, 2004), a model designed especially for forest fire modelling (Mutlu et al., 2008). FARSITE (Finney, 1998) is a fire growth simulation model which describes the spatial and temporal spread of fire in forests and rangelands using the spatial information on weather conditions, fuel type and topography (Halada et al., 2006, Carmel et al., 2009, Arca et al., 2005, Rothermel, 1983, Finney, 1998, Stratton, 2004, Arca et al., 2007).

The model requires five spatial raster layers namely slope, aspect, elevation, fuel model and canopy cover percentage (Carmel et al., 2009, Finney, 1998, Finney, 2004, Ryu et al., 2007, Stratton, 2004). Non-spatial data which is also required by the model include records of temperature, relative humidity, precipitation, wind speed and direction during the fire event. The functions of the input data used in this study are shown in Table 3-2. The FARSITE fire model requires the spatial resolution of the raster data to be between 25-55m (Finney, 1998) because it has been shown that at this spatial resolution an acceptable level of detail is achieved in the simulation results. This therefore indicates that the model minimizes computation problems but at the same time achieving realistic results.

Table 3-2: Inputs used in FARSITE fire model and their functions

Input	Function
Elevation	For adiabatic adjustment of temperature and humidity
Slope	For the computation of direct effects on fire spread
Aspect	Together with latitude, date and time of the day, it determines the angle of incident solar radiation
Fuel model	Describe physical characteristics of the fuel that are used to determine surface fire behaviour
Canopy cover	Determines the average shading of surface fuels and affects fuel moisture calculations. It also reduces wind speed and affects surface fire
Temperature	Influences fuel moisture
Wind speed and direction	Influence fire spread
Precipitation and Humidity	Determines fuel moisture content and rate of spread

Adopted and modified from (Ryu et al., 2007, Carmel et al., 2009, Finney, 1998)

The preparation of these input layers is described in the following sections.

3.3.2.1. Image classification

Sampling of field points

Random points were generated in ArcGIS software using stratified random sampling technique. An iPAQ GPS was used in the field to locate the random points (Appendix 14). At each random point the dominant vegetation cover type was noted. The sampling points were divided into training and test samples. This was important for the classification of the satellite imagery.

Supervised classification

Remote sensing data provides information about the fuel conditions through the identification of vegetation before the fire (Perry, 1998). An othorectified, cloud-free ALOS satellite imagery acquired on the 15th of July 2007 was used for classification. This image was chosen based on both the availability and its high spatial resolution (10m). The image was acquired just a week before the fire event occurred and it is assumed that it is a good representation of the vegetation characteristics before the fire occurred. This is essential for the classification of land cover types and for fuel type mapping because fuel types depend on vegetation. It is important in fire modelling to have accurate classification in order to better represent the fuel status (Mutlu et al., 2008). An aerial photograph acquired in June 2007 was also used for the confirmation of ground truth points for the classification. This was important because the field campaign was done two years after the fire had occurred, and confirmation of the ground points using the aerial photograph would improve classification. According to (Lillesand and Kiefer, 2004) imagery of high spatial resolution can be used for collecting ground truth points for classification.

A land cover map was generated in ERDAS IMAGINE by supervised classification of the orthorectified ALOS satellite imagery using the maximum likelihood classification algorithm (Lillesand and Kiefer, 2004). This algorithm is suggested to be the most suitable for vegetation mapping (Doma and Suzen, 2006). Training of the classification was done using the 139 observation points collected during fieldwork whilst the assessment of the classification was done using the other 157 points. The user accuracy and producer accuracy were calculated for the classification. To determine the extent to which the classification surpassed the random assignment of pixels (Lillesand and Kiefer, 2004), Kappa statistic was computed. The classified image was resampled to the same spatial resolution (30m) with the DEM which is required by the model (Stephens, 1998).

3.3.2.2. Canopy cover estimation

Canopy cover determines the average shading of surface fuels and affects the fuel moisture (Miller and Yool, 2002). Circular sampling plots ($500m^2$) were allocated at each random point within forests. Within each sampling plot, percentage canopy cover was estimated using a spherical densiometer. Five readings were taken in each plot (N, S, E, W and centre) in order to minimize bias. The average canopy cover for each plot and also for each cover type was then computed (Mbow et al., 2004). The classified ALOS image was reclassified according to percentage canopy cover as shown in Appendix 1. The percentage canopy cover map was converted to ASC11 format and then exported for input in the FARSITE model.

3.3.2.3. Fuel model selection

Fire behaviour models require the descriptions of fuel properties in the form of fuel models (Anderson, 1982). Fuel models refer to vegetation communities which have been grouped by their similar potential fire behaviour (Mutlu et al., 2008). They are described by their fuel parameters such as load, bulk density, particle size, heat content and moisture of extinction (Anderson, 1982, Arroyo et al., 2008, Scott and Burgan, 2005, Mutlu et al., 2008, Miller and Yool, 2002). These fuel models are characterized by a set of numerical values describing the fuel parameters. Fuel models are therefore a key input in fire models (Mutlu et al., 2008) to predict fire spread behaviour (Rothermel, 1972, Andrews, 2009, Andrews and Queen, 2001, Anderson, 1982).

53 standard fuel models have been developed for the Rothermel (1972) fire spread model. These include the original 13 fuel models described by Anderson, 1982 and the recent 40 (Appendix 2) which were described by Scott and Burgan, 2005. It is anticipated that recent fire modelling makes use of the new fuel models rather than the first 13 models (Scott and Burgan, 2005). These recent fuel models are described in terms of the physical characteristics of the fuel (Andrews and Queen, 2001, Scott and Burgan, 2005) unlike the previous models which were described in terms of vegetation or species types (Anderson, 1982). This allows the recent fuel models to be applied in many vegetation types. The naming of the fuel models has been based on the fire-carrying fuel type (Scott and Burgan, 2005) such as grass, grass-shrub, shrubs, timber or non-burnable.

In some cases custom fuel models have to be developed when the standard fuel models (Anderson, 1982, Scott and Burgan, 2005) does not match well with the vegetation characteristics in the studied area. The development of custom fuel models therefore involves adjustment of the fuel parameters as observed in the field. The standard fuel model might fail to describe the fuel load or the fuel moisture properly and it will be necessary to change such parameters. These parameters should therefore be based on field observations.

It is essential in fire modelling to have accurate information about the fuel status (Arroyo et al., 2008). The appropriate selection of fuel models is crucial for realistic fire modelling (Anderson, 1982). Selection of suitable fuel models is done based on the similarities between the observed vegetation characteristics and the description of the previously developed standard fuel models (Anderson, 1982, Scott and Burgan, 2005). In this study, standard fuel models were selected from those developed by (Scott and Burgan, 2005) based on the similarities between the fuel / vegetation characteristics observed in the field and the model description. The vegetation cover types as classified in the ALOS imagery were reclassified according to the selected fuel model based on the fuel status as observed in the field. Table 3-3 below shows the reclassification of the vegetation cover types according to the most suitable fuel model and the map is shown in Appendix 4.

Table 3-3: Description of fuel models used in the simulation

Observed cover type	Fuel model name, code and description	Number	Fuel description
Abandoned farmlands	**Grass (GR4)** Nearly pure grass and/or forb type	104	Moderately coarse continuous grass, average depth about 2 feet.
Beech	**Timber Litter (TL6)** Dead wood fuel (litter) beneath a forest canopy	186	Moderate load, less compact.
Pine	**Timber-Understory (TU5)** Grass or shrubs mixed with litter from forest canopy	165	Fuel-bed is high load conifer litter with shrub understory.
Mixed forest	**Timber-Understory (TU3)** Grass or shrubs mixed with litter from forest canopy	163	Fuel-bed is moderate litter load with grass and shrub components.
Bare	**Non-burnable (NB)** Insufficient wildland fuel to carry wildland fire under any condition	99	Bare ground

Source: Scott and Burgan (2005)

As shown in Table 3-3 fuel models have been described by the fuel that carries fire namely, grass (GR), timber litter (TL) and timber understory (TU) with their respective codes. Although there is no fuel to burn in bare area, fire models have been developed with the name non-burnable (NB). This description of fuel models is based on the physical characteristics of the fuel (Dimitrakopoulos, 2002). The fuel model allocated to the beech forest is characterized by just dead litter in the forest understory.

The fuel characteristics of the selected fuel models were the most closely related to the fuel characteristics observed within the study area during fieldwork. The photographs which were taken during the fieldwork to help in fuel model selection are shown in Figure 3-5.

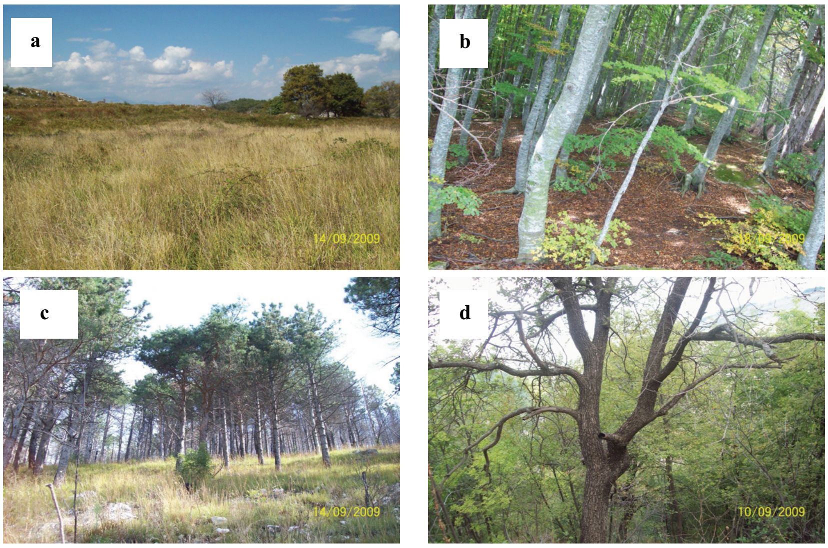


Figure 3-5: Pictures showing the fuel characteristics
a) abandoned farmlands (X,Y: 421511,4675533) b) beech forest (X,Y:424575,4669120) c) pine forest(X,Y:424293,4672249) d) mixed (broadleaf-deciduous) forest (X,Y:421136,4673839)
Source: Author (September 2009)

The forest floor characteristics were also observed during the fieldwork and photographs were taken as shown in Figure 3-5. The numerical values of the fuel model parameters used in the simulation are shown in Appendix 3. These values were used as derived from the selected standard fuel models because no field measurements were taken for those parameters.

3.3.2.4. Topography

Topography is also an important determinant of the behaviour of fire. Elevation and aspect determine the variation in the fuel moisture in dead or live fuel. The rate of spread and intensity of fire increase with increase in upward slope (Salis, 2008). This leads to faster rate of spread due to more rapid heating of the fuel particles and hence producing larger fires with higher intensity (Finney, 1998). Aspect refers to the direction which the topographical relief is facing. It influences the amount of solar radiation where south and south-west–facing slopes usually receive more solar radiation than north-facing slopes in the Northern Hemisphere. This increases the fuel temperature and hence less energy is required to ignite the fuel (Salis, 2008). North facing slopes are more shaded which results in higher relative humidity and hence higher fuel moisture than south-facing slopes. Some topographic features such as valleys act as barriers to fire spread which slow or stop the spread of fire.

Topographic data (elevation slope and aspect) was derived from a digital elevation model (DEM) (30m) of the area using the Spatial Analyst tool in ArcGIS software. The layers were converted to ASC11 format for input into FARSITE model.

3.3.2.5. Weather Data

The combination of weather and fuel conditions has a influence on the behaviour of fire. Extreme weather conditions can affect the moisture status of fuels thereby influencing the probability of burning (Arca et al., 2006). The weather aspects which determine fire behaviour include temperature, precipitation, relative humidity, wind speed and wind direction (LaCroix et al., 2006).

Fuel moisture is determined by the amount, frequency and duration of precipitation. Heavy precipitation results in high fuel moisture and reduces the probability of burning and also the spread of fire (LaCroix et al., 2006). High relative humidity will result in moisture moving into the fuel and reduces the probability of burning and hence the fire spread behaviour. Low relative humidity promotes the spread of fire. Temperature also influence fuel moisture status (Mbow et al., 2004). The variation in fuel moisture is also determined by exposure to wind and sun.

Wind provides oxygen for burning and also contributes in the drying of fuels and increase fuel preheating for ignition. The direction of the prevailing wind influences the shape and intensity of fire whilst the strength of the wind influences the rate of fire spread and its intensity (Finney, 1998). Although wind speed and fire spread are related, the relationship is non-linear such that a small change in wind speed can give a larger change in fire spread (Rothermel, 1972). The variation in fire behaviour can be due to changes in wind direction and speed as determined by terrain (Forthofer and Butler, 2007, Forthofer, 2007).

In this study temperature, wind speed, wind direction, relative humidity and precipitation data at the time of the fire event was acquired from ‘‘Punta dell’est’’ Roccacaramanico (42° 06' N, 14° 01' E) (van Gils et al., 2008). This is the closest functional weather station to the study area as shown in Appendix 11. It was assumed that there is no significant variation in weather conditions between the study area and the weather station since both the weather station and the fire scar lie on the same seaward facing side (van Gils et al., 2010) and at a comparable altitude (1050m). The weather data per every 30minutes was converted to text format before input into the FARSITE model.

3.3.2.6. Barriers to fire spread

FARSITE assumes that the spread of fire is dependent on fuel type and load hence the model does not have a function to extinguish fire automatically. As long as there is fuel, the model assumes that the fire is spreading (Ryu et al., 2007). In this study roads and valleys were used as barriers to fire spread hence minimizing the overestimation of the fire spread.

The barriers to fire spread in form of roads and valleys as shown in Appendix 5 were observed during fieldwork. This was based on observations such as in Figure 3-6 where one side of the road had signs of burning. Similar observations were made with some of the valleys as shown in Figure 3-6a. The barriers were digitized from the aerial photograph for use as barriers in the model simulations (Appendix 5).

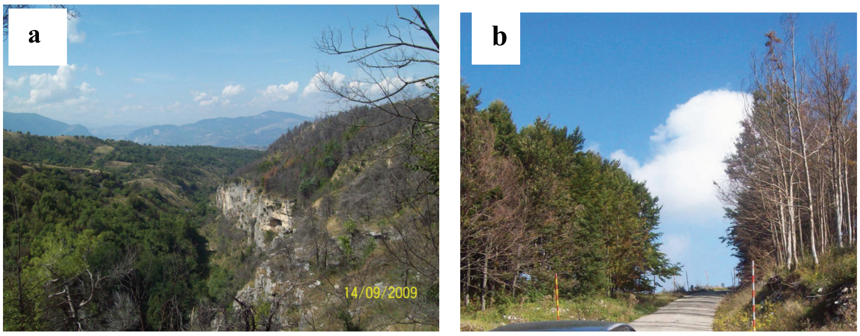


Figure 3-6: Photographs showing barriers to fire spread in the form of a) valleys (X,Y:422758,4673294) b) roads (X,Y:424671,4669547)

3.4. Fire Spread Simulation

3.4.1. Details of the fire

In July 2007 a fire occurred in the Majella National Park. The park management states that the first observation of the fire was made on the 22nd of July around 1500 to 1530h but the exact date and time for the end of the fire spread was not given as described in Appendix 8. MODIS active fire dataset (van Gils et al., 2010) indicate that the fire was first detected by MODIS Terra on the 23rd of July at 2050 in the abandoned farmland. On the 24th of July at 0100 MODIS Aqua detected fire in the pine plantation, beech forest and other new fire locations in the abandoned farmland. The last detection of the active fire was at 21.35h on the 24th of July. This information (Appendix 6) was useful as guidance in determining the final date of the simulation. The duration of the fire was therefore considered to be between the 22nd to the 24th of July. It was assumed that after the 24th any smouldering below the leaf litter as indicated by the park management did not result in any significant expansion of the fire scar. The smouldering is assumed to have occurred within the burnt biomass and hence no further spread was occurring. The MODIS data was therefore preferred because the information is likely to have less human error. In most studies (Arca et al., 2007, Forthofer and Butler, 2007, Halada et al., 2006, LaCroix et al., 2006, Ryu et al., 2007) the fire duration is clear due the availability of well documented information about the fire. It is important to take note that information related to the details about the fire suppression activities which were taken was unavailable.

3.4.2. Weather conditions

The weather conditions during the fire event were characterized by high temperatures, with maximum temperature reaching 36.9^{0}C. The average wind direction was SSW whilst the maximum wind speed was 14km/hr. Table 3.4 shows the weather characteristics observed during the fire event. There was no precipitation during the whole month when the fire event occurred. This indicates that it was a dry period.

Table 3-4: The weather conditions during the fire event

Weather parameter	Data
Maximum Temperature (0C)	36.9
Minimum Temperature (0C)	33.6
Precipitation (mm)	0
Maximum Wind Speed (km/hr)	14
Average Wind Speed (km/hr)	9.5
Average Wind direction	SSW
Average Relative Humidity	44

Source: ''Punta dell'est'' Roccacaramanico weather station

3.4.3. FARSITE Simulation

The fire spread simulation was done in 30 minute time steps in FARSITE using the spatial and non-spatial data. A time step is the maximum amount of time that the environmental conditions are assumed constant (Finney, 1998). Several simulation trials were done to test the behaviour of the fire. In all the simulations the starting time of the fire was 1200 on the 22nd of July, three hours before the first observation by the park management. It was assumed that it is likely that the fire was already burning for a while before their detection. The simulation end time was set at 2359 on the 24th of July. This was based on the observation by MODIS Terra satellite which detected the last active fire (Appendix 6) in the park at 2135 on the 24th of July.

The crown fire function was enabled. It is important to note that FARSITE does not allow the assignment of crown fire activities in a single cover type but applies it to all fuels together. Crown fire was only expected in the pine forest (van Gils et al., 2010). However this was taken care of by the fact that the fuel model for the mixed forest involved only surface fire. The selection of a fuel model for the beech forest assumed that fire spread was within the forest litter. Crown fire therefore only occurred in the pine forest (van Gils et al., 2010) which also agreed with the field observations.

The main aim of the simulation in FARSITE was to simulate fire scar that matches as closely as possible to the observed fire scar. This was therefore done in steps. The simulation in FARSITE was done step by step with adjustment of environmental variables, starting from a generalized model to gradually a more customized model. The adjustments were done on the rate of fire spread and also on the wind data. Although FARSITE has the function for fire suppression activities, this was not considered in all simulations because there the information was unavailable.

3.4.3.1. Simulation with spatially uniform wind

Simulation without rate of fire spread adjustment

The first simulation was done to test whether the model could simulate the fire showing some resemblance with the observed fire scar. The applicability of the model was tested first by varying the simulation duration and keeping constant topography and weather conditions. The simulations were done using the input data as described in the preceding sections. The first simulation was done from the 22-24th of July. Simulations were repeated by increasing the simulation duration by one day as shown in Table .3-5 which shows the settings used in FARSITE during the simulations.

Table 3-5: FARSITE settings used during the simulations

	Simulation 1	**Simulation 2**	**Simulation 3**	**Simulation 4**
Model time step(min)	30	30	30	30
Perimeter resolution (m)	30	30	30	30
Distance resolution (m)	30	30	30	30
Crown fire enabled	Yes	Yes	Yes	Yes
Simulation start date	22July (1200)	22 July (1200)	22 July (1200)	22 July (1200)
Simulation end date	24July (2359)	25 July (2359)	26 July (2359)	27 July (2359)

This was mainly done to check how the fire would behave at a longer duration. Maps of fire perimeter and fireline intensity were derived from the simulation. An interpreted ignition point was incorporated in all the simulations. The process of interpreting this ignition point is described in detail in Section 3.5.3.

Simulation with rate of fire spread adjustment

At this stage the rate of fire spread was adjusted for some of the fuel models. This adjustment of rate of fire spread by model users allows for the fine tuning of spread rate to expected fire spread patterns (Duguy et al., 2007, Finney, 1998). It is important to note that in this study the decision of the adjustment factor was based on ‘trial and error’. The decision to adjust the rate of fire spread was based on field observations which indicated that the characteristic of the fuel in the grass and pine forest indicated that fire in those areas may be of higher spread rate than in the beech and mixed forests. The grass and pines are known to be susceptible (Cardille and Ventura, 2001, Ryu et al., 2007) to fire. Adjustment factors of 1.5 and 1.1 were therefore applied on the rate of fire spread in the grass and pine respectively. The adjustment factors were also applied in relation to other studies (Arca et al., 2007, Duguy et al., 2007). Carmel et al., 2009 incorporated adjustment factors based on field observations and on other studies. They used an adjustment factor of 4 for pine forest using Anderson (1982) fuel model 10. It is also worth to take note that the adjustment of the rate of fire spread is fuel model specific. The adjustment factors were therefore applied on fuel model 104 (grass) and 163 (pine).

The simulation in FARSITE was done incorporating the adjustment and keeping all other input data constant. The simulation in FARSITE gave outputs consisting of maps of fire perimeter, fireline intensity. From this step onwards the simulation duration was fixed at 22-24th July.

3.4.4. Incorporation of spatially varying wind

3.4.4.1. Wind modelling

Wind behaviour varies spatially especially in complex terrain environments. It is important to capture such variation when simulating fire behaviour. Fire simulation models such as FARSITE do not take into account this spatial variation in wind behaviour. Wind models such as WindWizard (Forthofer and Butler, 2007) and WindNinja (Forthofer, 2007, Forthofer and Butler, 2007) have been developed for such tasks. Simulation of wind behaviour based on terrain is therefore essential in complex terrain (Forthofer and Butler, 2007, Forthofer, 2007) such as Majella National Park.

The spatial variation in wind speed and direction as determined by variation in topography was simulated in WindNinja (Forthofer, 2007) model. WindNinja is a computer program which computes spatially varying wind fields for wildland fire application. The data required for the wind model includes elevation (DEM), mean initial wind speed and direction and specification of the dominant vegetation in the study area. The wind behaviour simulation therefore accounts for the influence of elevation, terrain and vegetation on the general wind flow. The outputs of the wind model include geo-referenced raster grids and shapefiles of wind speed and direction. Raster grids are used in spatial fire behaviour models such as FARSITE and FlamMap. The shapefiles are usually required for plotting the wind vectors in GIS programs.

The elevation data used in this study was a digital elevation model (DEM) with a spatial resolution of 30m. The resolution was assumed to give adequate resolution for wind flow and at the same time minimizing computation time. The wind speed and direction at 30 minute interval was input into the wind model. The model simulations were done at 30 minute time steps.

Simulation without rate of fire spread adjustment

The output gridded wind from Wind Ninja was input into FARSITE, replacing uniform wind data. The other parameters were kept constant to determine the effect of spatially varying wind data on the fire spread behaviour. The simulation in FARSITE gave outputs consisting of maps of fire perimeter and fireline intensity

Simulation with rate of fire spread adjustment

The rate of fire spread was adjusted on the fuel models for grass and pine respectively as described in section 3.4.3.1. Simulation in FARSITE was therefore performed.

3.5. Accuracy Assessment

3.5.1. Fire extent

The accuracy of the simulations was determined by the level of similarity between the simulated and the observed fire scar. The observed fire scar in this study was a fire scar map produced from a ground survey by the park management (van Gils et al., 2010). The fire scar was produced by GPS mapping a month after the fire occurred. The simulated fire scar vector map was converted to raster format and reclassified into burned and unburned areas. The same procedure was done for the observed fire scar. The reclassified maps were overlaid using the Spatial Analyst tool in ArcGIS. The agreement and the difference in area were calculated. The percentage accuracy of the simulation was therefore calculated. Figure 3-7 shows the details of the processes which were taken in the assessment of the accuracy of the simulation.

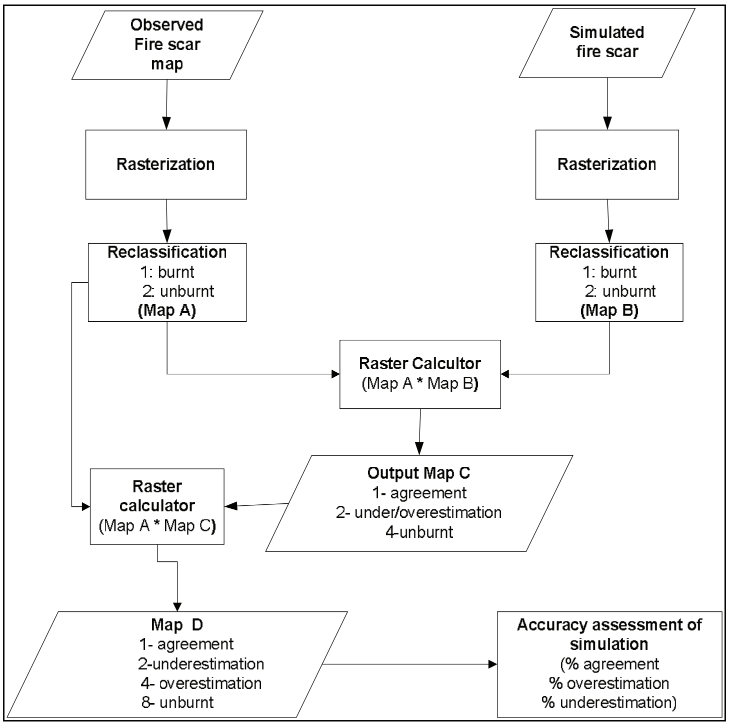


Figure 3-7: The accuracy assessment procedure

3.5.1.1. Tests for similarities

An error matrix was calculated between the simulated and observed fire area to determine the frequency of absence or presence of burned areas. Two statistical indicators were derived from the error matrix in order to test the accuracy of each simulation. The Sorensen's (Legendre, 1998) and the Cohen's Kappa (Congalton, 1991) Coefficients were calculated for the simulations.

Sorensen's coefficient

The Sorensen's (Zuur et al., 2007, Legendre and Legendre, 1998) coefficient (SC) is an asymmetric index (Zuur et al., 2007) which was used in this study to indicate the exclusive association between the simulated and the observed fire scars. The coefficient has been applied as an indicator of the association between observed and simulated fire scars under Mediterranean conditions in Italy by Arca et al., 2007.

Cohen's kappa statistic

To assess whether the agreement between the simulated and observed fire scars was not due to chance, Cohen's (Congalton, 1991) kappa coefficient was calculated. This non-parametric measure of classification accuracy (Arca et al., 2007) was used to evaluate the agreement between the simulated and observed fire scar after the removal of agreements by chance.

3.5.2. Spatial distribution of fire intensity

One of the outputs from FARSITE is a fireline intensity map which shows the amount of heat energy released per unit time. This was therefore used as an indicator of fire intensity. In fire science there is no standard classification of fireline intensity. Previous studies (Dimitrakopoulos, 2002, Dwomoh, 2009) have used their own thresholds to classify fireline intensity. In this study the classification of fireline intensity was based on the description by Rothermel (1984) as shown in Figure 3-9.

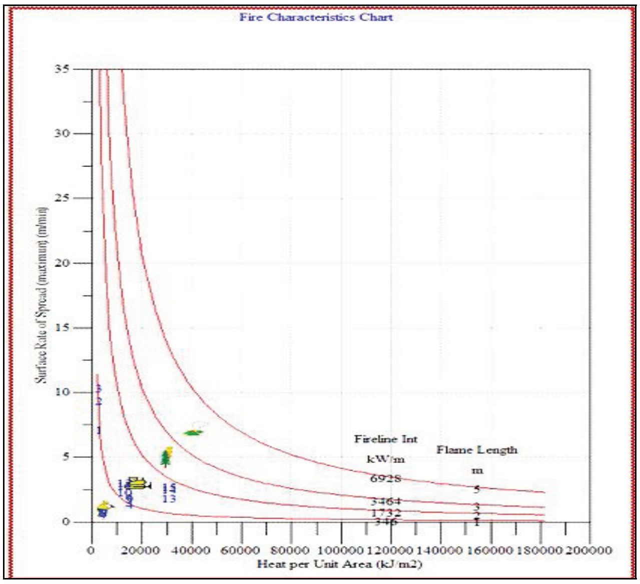


Figure 3-8: The classification of fireline intensity

Source: Rothermel (1984)

This was considered to be reliable guidelines because the intensity of fire is related to the methods of fire suppression. In low fireline intensity, the suppression can be done by humans whilst as the intensity increases air attack would be required (Rothermel, 1984). The simulated fireline intensity was related to the MODIS data and also the ground observations.

3.5.3. Identification of possible ignition points

The simulation of a fire event in FARSITE model requires an ignition point as a starting point of the fire spread. There was insufficient and conflicting information about where the fire started. Hence this study utilised the information in the simulation to investigate more about the possible single or multiple ignition points in light of conflicting evidence.

3.5.4. Multiple ignitions

The first opinion was that the fire may have been due to multiple ignition points. These included picnic areas and areas along roads. During the fieldwork in September 2009, locations which were considered to be likely ignition points were identified. These included picnic places and areas along roads. The geographic locations of the points were recorded using the IPAQ GPS. MODIS data was also incorporated into the likely multiple ignition points. Table 3-6 and Appendix 7 show the location of points used for testing multiple ignition points.

Table 3-6: The list of multiple ignition points tested

X	Y	Source	Number	Time	Date
425251	4672221	ground observation			Sep-09
423582	4676122	ground observation			Sep-09
425038	4669508	ground observation			Sep-09
422758	4673294	ground observation			Sep-09
423266	4675861	ground observation			Sep-09
424293	4672249	ground observation			Sep-09
421698	4670793	MODIS Terra	1	2050	23-07-2007
423976	4671311	MODIS Terra	2	2050	23-07-2007
422201	4671503	MODIS Terra	3	2050	23-07-2007
423059	4672775	MODIS Aqua	4	100	24-07-2007
424449	4669566	MODIS Aqua	5	100	24-07-2007
422231	4672139	MODIS Aqua	6	100	24-07-2007
423443	4672908	MODIS Aqua	7	100	24-07-2007
422408	4673115	MODIS Aqua	8	100	24-07-2007
424005	4672021	MODIS Terra	10	1025	24-07-2007
424345	4673233	MODIS Terra	11	1025	24-07-2007
422941	4673662	MODIS Terra	12	1025	24-07-2007
424257	4671503	MODIS Aqua	13	1205	24-07-2007
424079	4672509	MODIS Aqua	14	1205	24-07-2007
422926	4673322	MODIS Aqua	15	1205	24-07-2007
422734	4674298	MODIS Aqua	16	1205	24-07-2007
421831	4674727	MODIS Terra	17	2135	24-07-2007

The first FARSITE simulation trials were done using these points with the assumption that the fire had multiple ignition points. The most possible ignition point was considered to be the one that would give a simulated fire scar that closely resembles the observed fire scar as mapped by the park management.

3.5.5. First Information from park

Information about where the fire could have started was provided by the park management. They indicated that the first observation of the fire was made at the right side of the road to La Majelletta, right after the junction with the road to Santo Spirito hermitage. The exact location in form of geographic coordinates was however not provided. This information suggested that the fire may have been due to a single ignition point. Figure 3-9 shows the location of the junction to Santo Spirito and the points which have been tested as single likely ignition points. Several simulations were therefore performed by gradually moving the ignition point around the junction until a good fit was reached. The ignition point which resulted in the best fit is shown in Figure 3-10. This final suggested ignition point was then used for all the simulations. It was therefore referred to as the 'interpreted ignition point'.

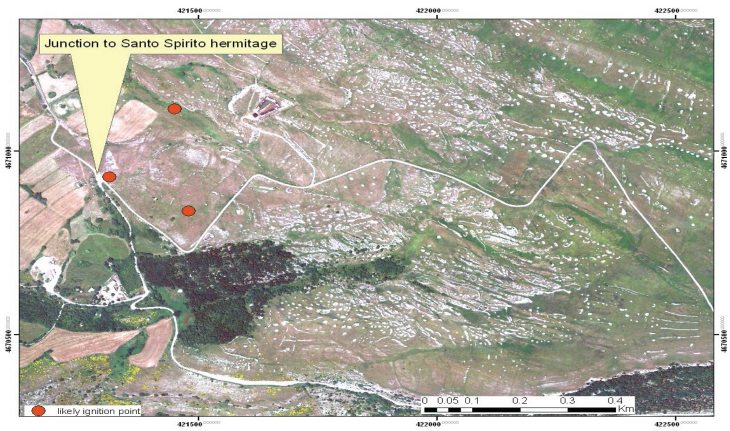


Figure 3-9: The likely ignition points which were tested

The likely ignition points indicated in figure 3-10 were utilized in simulations to test their likelihood. The interpreted ignition point which resulted in a simulated fire scar which was the most similar to the observed fire scar was considered to be the most likely ignition point (Figure 3-10) based on the given information.

Figure 3-10: The final interpreted ignition point
The background is an aerial photograph of 2007 acquired before the fire. (SOURCE: Majella National Park)

'True' ignition point

Later during the research period information about the geographic location was provided by the forest guards through the park management. This point, which is about 1 km away from the interpreted ignition location (Figure 3-11) was considered to be the 'true' ignition point. The simulated fire scars using the interpreted and true ignition points were compared.

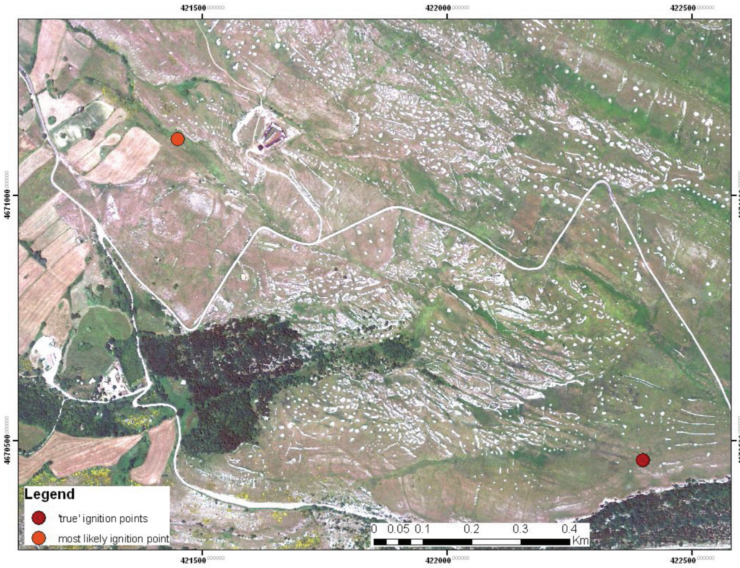


Figure 3-11: The location of ignition points used in the study

4. Results

4.1. Land cover Classification

The supervised classification of the ALOS imagery derived five cover types from the study area. These include bare ground, beech forest, pine forest, mixed forest and grass. The mixed forest refers to the combination of pubescent oak and hop hornbeam forests. The map of the classified land cover types is presented in Figure 4.1.

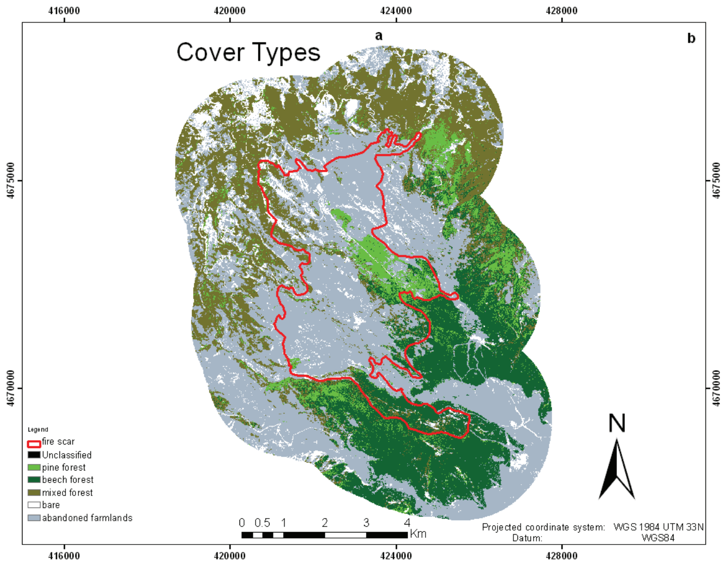


Figure 4-1: The land cover types within the study area. The red boundary shows the outer boundary of the fire scar.

The description of the cover types and their proportions within the study area is presented in Table 4. 1.

Table 4-1: Description of the land cover types

Cover Type	Proportion (%)	Description
Beech	19	Monospecific beech forest *(Fagus sylvatica)*
Pine	8	Monospecific plantation of pine *(Pinus Nigra)* species
Mixed forest	22	Combination of pubescent oak (*Quercus pubescens Willd*) and hop-hornbeam (*Ostrya carpinifolia Scop*) trees
Abandoned farmlands	43	Abandoned farmlands, crop fields and pastures (later referred to as abandoned farmlands)
Bare	8	Non-vegetated area mainly roads, built up and rocky areas

The highest proportion (43%) of the study area is covered by grass which is mainly abandoned farmlands, crop fields and pastures (van Gils et al., 2010) whilst pine forest and bare area cover the least proportion of the area. Figure 4.1

4.1.1. Accuracy assessment

The overall accuracy of the land cover classification was 84% whilst the overall Kappa statistic was 0.83. The summary of the results of the accuracy assessment is presented in Table 4.2.

Table 4-2: Summary of the accuracy assessment of the land cover classification

	Reference totals	Classified totals	Number correct	Producer accuracy	Users Accuracy
Pine	30	31	26	86.67	83.87
Beech	30	31	26	83.87	83.87
Mixed	31	28	24	75	85.71
Bare	31	35	28	84.85	80
Grass	35	32	28	71.79	87.5
Total	157	157	132		
Overall Accuracy			**0.84**		
Overall Kappa Statistic			**0.83**		

The producer's accuracy was highest in pine class and lowest in the grass class. The overall accuracy indicates the proportion of pixels which are correctly classified. The user's accuracy on the other hand indicates the proportion of pixels that are classified correctly which really belong to that class in reality (Oki et al., 2006). The Kappa coefficient indicates the level at which the correct classification is not by chance (Lillesand and Kiefer, 2004).

4.2. FARSITE Fire Behaviour Simulation

Figure 4-2 shows an example of the FARSITE interface. The background is the land cover map.

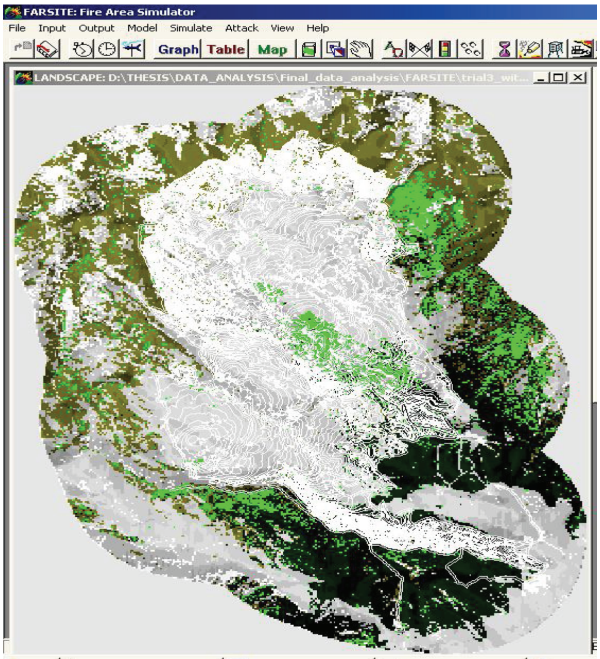


Figure 4-2: An example of the simulation in FARSITE.

The white lines known as fire perimeter lines show how the fire progresses within the landscape. The distance between the lines indicate the distance covered by fire in each time step (30 minutes). Figure 4-2 shows that in the abandoned farmlands, the fire spreads for longer distance within each time step than in other vegetation types. This indicates a higher rate of fire spread probably due to the fine fuel particles of the grass vegetation. In the beech and the mixed forests the rate of fire spread is lower than in the grass and pine plantation as indicated by shorter distance between the fire perimeter lines.

4.2.1. Simulation with spatially uniform wind

4.2.1.1. Simulation without adjustment of rate of spread

Figure 4-3 shows the fire spread scenarios over the study area. The behaviour of the model was tested first by extending the simulation duration. The extent of fire increases with the increase in the simulation duration as shown in Figure 4-3a-d. The first simulation in Figure (4-3a) demonstrates that the simulated fire was spreading in an expected pattern. However, the fire stops just after the abandoned farmlands. This led to the simulation with extended fire duration as shown in Figures 4-3b-d where the fire spreads up to the extent of the observed fire scar by the 27th of July. The extension of the simulation duration at this level was only used to test the behaviour of the model.

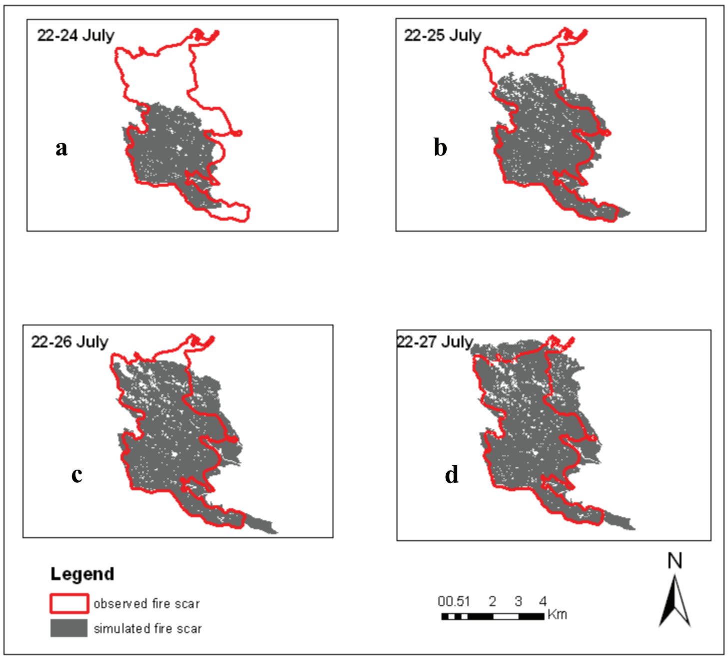


Figure 4-3: The extent of the simulated fire perimeter without any adjustment of rate of spread

All the simulations show that the fire was spreading in the North to North-Easterly direction and follow the shape of the observed fire scar. It is important to take note that the percentage agreement refers to the proportion of the observed fire scar which was simulated as burned. The level of agreement between the observed and the simulated fire scars increases as the simulation duration increases as shown in Table 4.3.

Table 4-3: The accuracy assessment of the fire simulation

Scenario	Agreement (%)	Underestimation (%)	Overestimation (%)
22-24 July (1200-2359)	49.97	50.03	5.54
22-25 July (1200-2359)	77.17	22.83	13.59
22-26 July (1200-2359)	90.24	9.76	21.09
22-27 July (1200-2359)	96.94	3.06	29.01

The first simulation with the observed fire duration (22-24 July) indicates that the agreement between the observed and simulated fire scars is only 50%. This was an underestimation of the observed fire scar and also did not correspond with MODIS active fire data which was used in this study as the guide for duration of the fire in the simulation. After five days of simulation the agreement between the simulated and the observed fire scars rises to 96% with the lowest underestimation but highest overestimation.

The pattern of spread and the shape of the simulated fire scar highlighted the possible applicability of the model in the study area because increasing the simulation duration resulted in increase in the agreement between the two scars as indicated in Table 4-3**.** However this is not realistic since the fire stopped on the 24th of July as indicated by MODIS data. The other simulations were therefore done from the 22nd to the 24th of July.

The Kappa and Sorensen's coefficient for the '22-24 July' simulation duration were 0.59 and 0.64 respectively. These statistics indicates moderate agreement between the simulated and observed fire scars.

4.2.1.2. Spatially uniform wind with adjusted rate of spread

The simulation at this level was from the 22nd to the 24th of July. The adjustment of the rate of spread had an effect of increasing the similarity between the observed and simulated scars to 75% whilst reducing the level of underestimation to 25%. This similarity level therefore indicates the proportion of the observed fire scar which was simulated as burned.

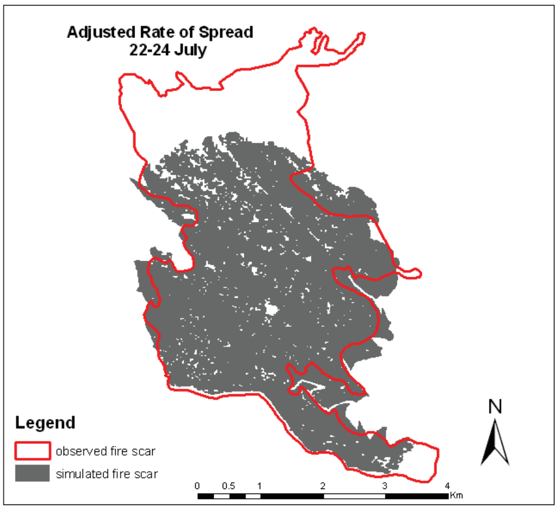


Figure 4-4: Simulation with rate of spread adjustment

The level of overestimation however increased to 11%. The Sorensen (Zuur et al., 2007) coefficient of 0.80 shows high similarity between the observed and simulated fire scars (Figure 4-4). Although the simulation improved, one MODIS active fire detected on the 24th of July at 2135 was still not included in the simulated burned area as shown in Figure 4-5.

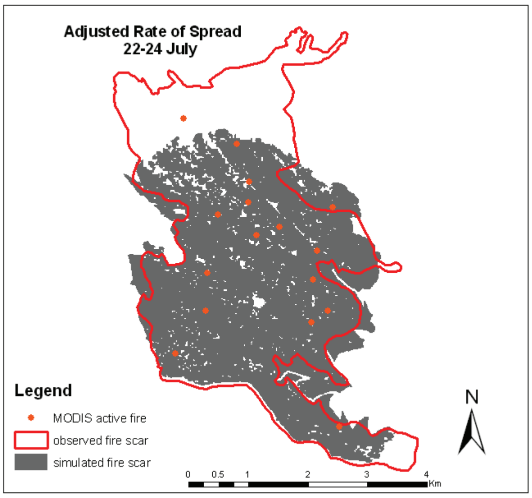


Figure 4-5: Simulation with rate of spread adjustment showing the observed MODIS active fire data

This indicates that the simulation can still be improved by adjusting another factor.

4.2.2. The impact of spatially varying wind

4.2.2.1. Example of wind model output

Figure 4-6 shows an illustration of the output from WindNinja wind model.

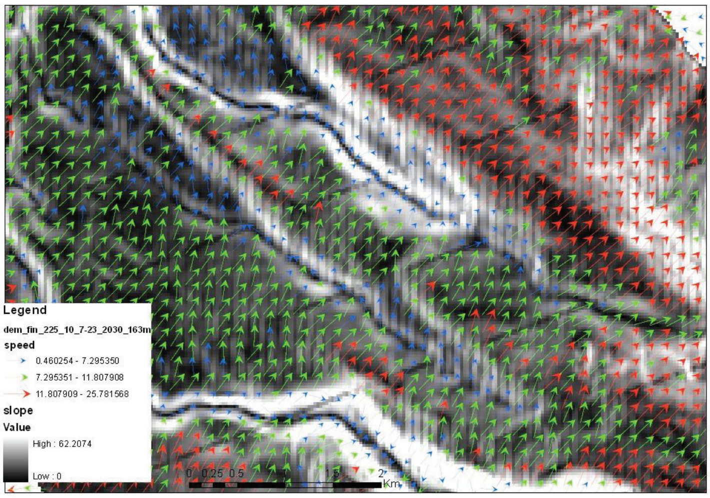


Figure 4-6: An example of the simulated spatially varying wind data

The arrows show the wind direction as determined by terrain. The colours of the arrows indicate the wind speed, blue (low), green (medium) and red (high). The wind is shown to be strongest on steep upslope. As indicated in Figure 4-6 the wind direction over the landscape is not uniform but it varies in space as determined by the terrain

4.2.2.2. Spatially varying wind without adjustment of rate of spread

Figure 4.7: shows simulated fire spread with the incorporation of spatially varying wind data. The map of simulation with spatially uniform wind has been displayed in order to visualize the difference from the one where spatially varying wind has been incorporated. The agreement between the simulated and observed fire scars increases from 50% (with uniform wind) to 95% (after incorporation of gridded wind).

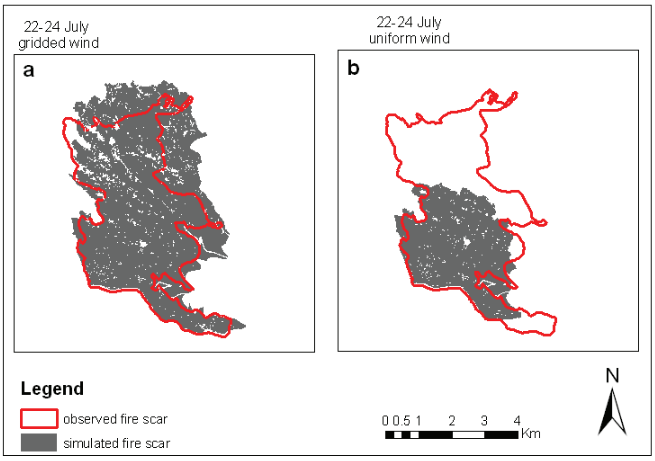


Figure 4-7: a) Simulation with spatially varying (gridded) data, b) Simulation with uniform wind data (for comparison)
The red boundary indicates the extent of the observed fire scar.

After the incorporation of spatially varying winds 95% of the observed fire scar was simulated as burned. This is also confirmed by the increase on Sorensen and Kappa Coefficients to 0.84 and 0.74 respectively. The extent of overestimation by the simulation however increased to 31% whilst the underestimation decreased to 5%. All the MODIS active fire data locations within the expected fire duration were included in the simulated fire spread.

In this case the MODIS data is being used as an indicator for the duration of active fire. Although the information from the park management states that the fire smouldering was still occurring in the burned area, we assume that the active fire ended around the same date as the last MODIS active fire detection. The MODIS active data set was useful to check the correspondence of the simulated fire scar with the real fire scar. Hence the incorporation of the spatially varying wind data improves fire simulation in FARSITE by increasing the rate of spread.The overestimation of the simulation with uniform wind was lower than that with spatially varying wind.

4.2.2.3. Spatially varying wind with adjustment of rate of spread

The simulated fire scar with the incorporation of fuel adjustment factors is shown in Figure 4-8.

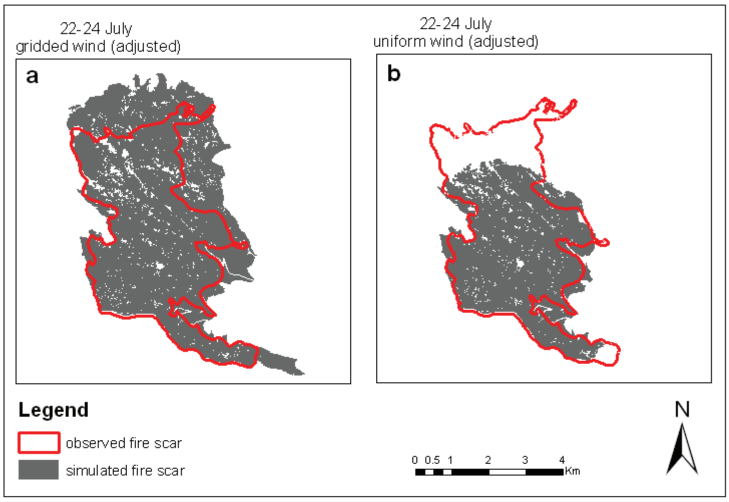


Figure 4-8: Effect of adjusting rate of spread a) simulation with spatially varying wind b)simulation with spatially uniform wind (for comparison)

The adjustment of the rate of fire spread on the simulation using spatially varying (gridded) wind data shows an increase in the proportion of the burned fire scar which was simulated as 'burned'. The similarity between the simulated and observed fire scars was 97% with the Sorensen's and Kappa coefficients of 0.84 and 0.74 respectively. These coefficients are the same as without the adjustment of fuel model.

4.2.2.4. Adjusting fuel on simulation with spatially varying wind

Figure 4-9 illustrates that the effect of adjusting fuel model on simulation with spatially varying wind is minor. This is supported by the similar values of the Sorensen's and Kappa coefficients with or without fuel adjustment.

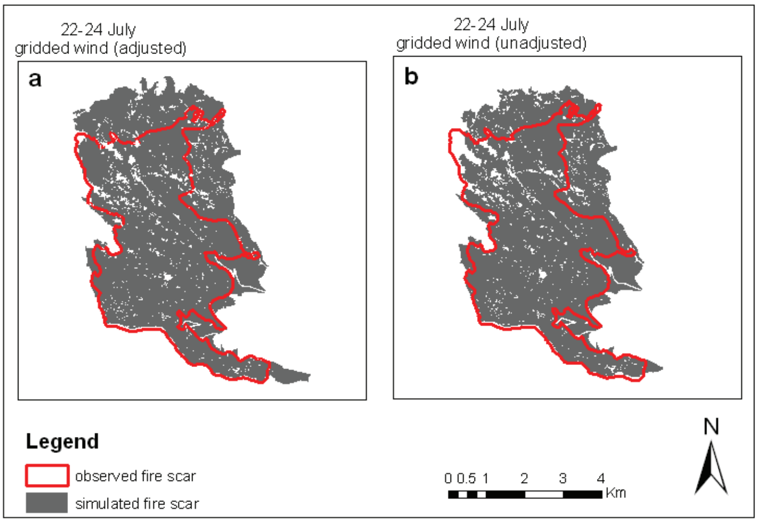


Figure 4-9: Effect of adjusting fuel on simulation with spatially varying wind a) adjusted b) unadjusted (for comparison)

4.2.2.5. Summary

Table 4-4 and Figure 4-10 illustrate the summary of the fire simulations from the different scenarios.

Table 4-4: The effect of fuel adjustment and spatially varying wind (22-24July)

	Uniform wind		**Spatially varying wind**	
	Fuel Un-adjusted	**Fuel Adjusted**	**Fuel Unadjusted**	**Fuel Adjusted**
% Agreement	50	75	95	97.5
% underestimation	50	25	5	2.5
% overestimation	5.5	11	31	35
Sorensen's Coefficient (SC)	0.64	0.8	0.84	0.84
Kappa	0.59	0.79	0.74	0.74

The results shown refer to simulations performed from 22nd (1200hrs) to 24th (2359hrs).

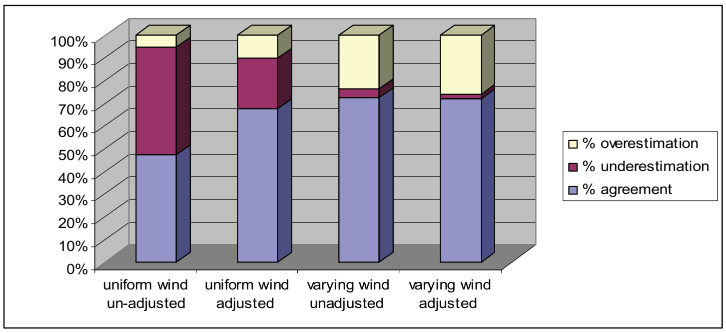


Figure 4-10: The results of the different simulation scenarios

The simulated fire scar under spatially uniform wind data had 50% similarity with the observed fire scar. The incorporation of spatially varying wind data resulted in an increase in the similarity between the fire scars. Wind has higher effect on the simulation results than adjusting the fuel model.

4.3. Spatial Distribution of fire intensity

The spatial distribution of fireline intensity within the fire scar is shown in Figure 4-11. The distribution of fire line intensity shows that fire of higher intensity occurred in the pine plantations. This agrees with the field observations where the tree trunks were charred and the plantation was almost burnt completely. A metal sign post (Appendix 10) within the pine plantation melted (van Gils et al., 2010) and also MODIS active data indicated that the points with the high fire intensity level were observed in the pine forest. Fire intensity was generally low in most parts of the study area. Most of the study area was characterized by low fireline intensity.

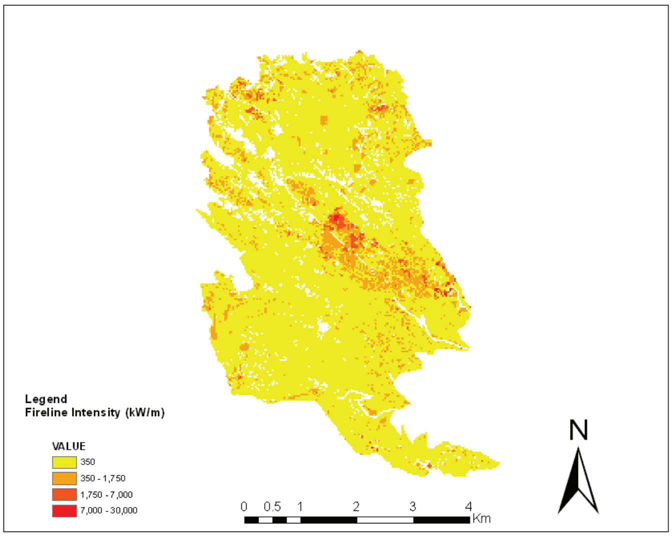
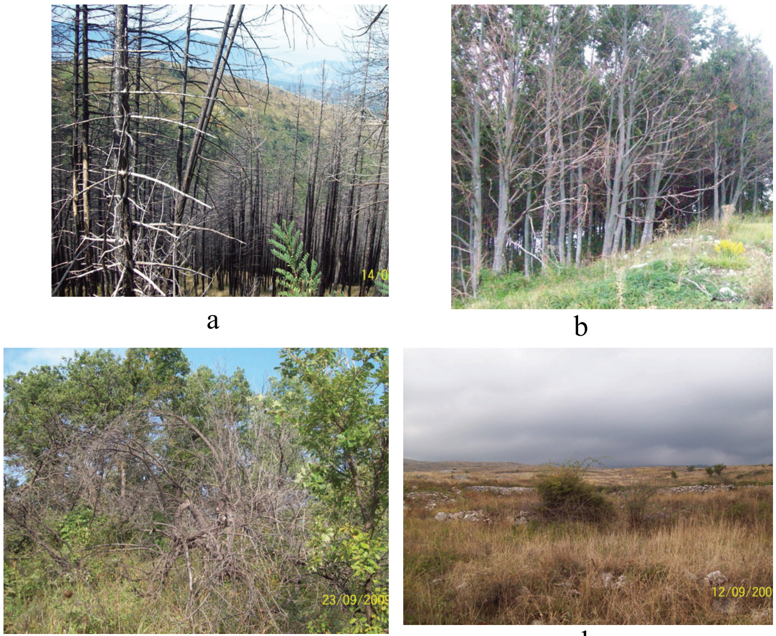


Figure 4-11: The spatial distribution of fire intensity

The fireline intensity as shown in Figure 4-3 above agrees to a great extent with the observations made during the field work. In the pine forest, for example, the tree trunks were charred as shown in Figure 4-12a. The charring of the trees could be an indicator that the fire was 'hot' meaning that it was of higher intensity. There was no charring in the beech forest (Figure 4-12b) indicating a fire of lower intensity. The bark of the beech trees is assumed to have dried over the two years because observations by van Gils et al., 2010 indicate that the leaves were still yellow during their study in 2008. Observations in the mixed forest (Figure 4-12c) and grass (Figure 4-12d) cover classes indicated a lower intense fire again. In the mixed forest only small branches and shrubs were burned whilst tree trunks had no sign of charring. In the grass only indications of dry shrubs showed that the fire was light. According to (Keeley, 2008) such field observations of the effects of fire on vegetation can be used to indicate the intensity of fire (Cumming, 2001).



a b c d

Figure 4-12: The observations of the severity of fire in the different land cover types a) pine (X:426201, X:4672047) b) beech (X:424466,Y:4669141) c) mixed forest (X:421947,4676107) d) grass (X:425222,Y:4673249)
Source: Author

Fire intensity is a representation of the energy that is released during a fire (Keeley, 2008) and is one of the measurements of fire intensity. It is positively correlated with fire severity. Fireline intensity is related to the impacts of fire on vegetation damage and mortality. Hence it is assumed that the field observations of vegetation damages could indicate the level of fireline intensity.

4.3.1. Identification of possible ignition points

Figure 4-13 shows the comparison between simulated fire scars using the suggested and true ignition points.

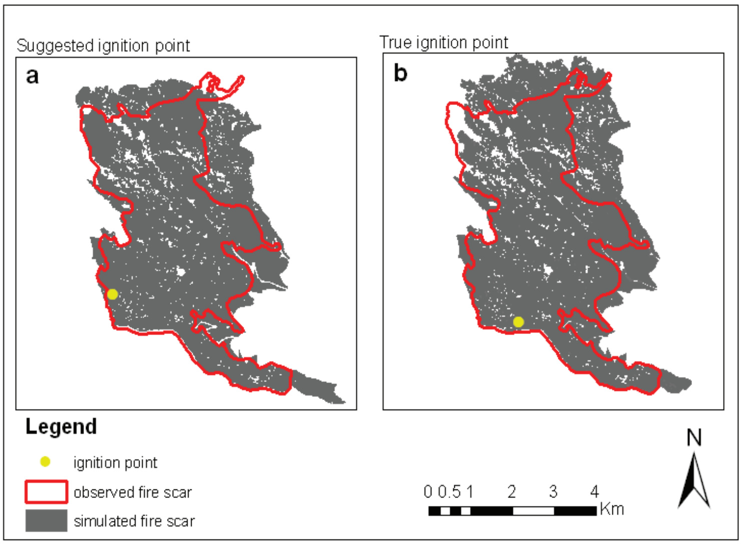


Figure 4-13: The comparison between simulation using different ignition points
a) interpreted ignition point b) 'true' ignition point

Some of the simulations with the ignition points which were tested are shown in Appendices 9. The simulation using the ignition point provided by the park management as shown in Figure 4-13b indicates that simulation using the suggested ignition point agrees well (90%) with the simulation using the real ignition point. This therefore shows that the model can be used to identify possible ignition points using provided information about the fire. This important function of the model can be utilised to confirm the given ignition point in any fire event. This will be useful in cases where arson is involved and the culprit can be identified.

5. Discussion of the Results

5.1. Supervised Classification

Although the classification of the satellite imagery was not one of the objectives of this study, it is an important process in fire spread modelling because it provides the basis for the fuel map. The classification derived a high Kappa statistic (0.83). This high accuracy of the classification also assures that the fuel mapping was reasonably accurate. The source of error can arise from error in choice of sample size, ground data collection accuracy, spatial auto-correlation and the classification algorithm used (Congalton, 1991). (Falkowski et al., 2005) mapped fuels in Moscow Mountain through classification with an accuracy of 0.63 (Kappa statistic = 0.54) and suggested that the map could be used in FARSITE for fire modelling. This therefore justifies that the classified imagery had sufficiently high accuracy for the reclassification according to fuel models and application in the FARSITE fire model.

5.2. Fire Simulation with Uniform wind

The simulations were done under four scenarios to test for the effect of adjusting the rate of fire spread on fuel models and the effect of incorporation spatially varying wind data in the model simulation.

5.2.1. Uniform wind and unadjusted fuel model

The simulation of the fire with uniform wind data resulted in 50% of the observed fire scar being simulated as burned. Although the pattern of spread and the shape of the simulated fire scar resembled that of the observed fire scar, the fire stopped within the grass whilst approaching the pine. This indicated an underestimation and this observation agreed with observations by (Fujioka, 2002) whose study showed that the simulation of fire with uniform wind data results in fire not growing to the extent of the observed fire scar.

The underestimation of the fire scar may be associated with errors in fuel models or the improper representation of local winds (Finney, 1998, Finney, 2004, Ryu et al., 2007, www-laep.ced.berkeley.edu/~itr/literature/farsite/, Forthofer and Butler, 2007). According to (Ryu et al., 2007) landscape heterogeneities may prevent the attainment of the maximum rate of spread hence resulting in underestimation of the fire spread area. It was therefore necessary to test the effect of adjusting the rate of fire spread and spatially varying wind.

5.2.2. Uniform wind and adjusted fuel model

The adjustment of the rate of fire spread resulted in the increase in the extent of the simulated fire scar hence increasing the similarity between the observed and simulated fire scars. The adjustment factor used in this study was lower than the one used by Carmel et al., 2009 but gave acceptable results. This could indicate that the fuel model chosen in this study greatly resembled reality. Overestimation by the simulation was higher when the rate of fire spread was adjusted. This error could have been associated with model assumptions or insufficient information provided for modelling.

Spatial and temporal resolution

The developers of the model (www-laep.ced.berkeley.edu/~itr/literature/farsite/) have indicated that simulations of fire spread at larger spatial and temporal scale can lead to overestimation. They have attributed this model weakness to the coarse spatial and temporal resolution used in the model simulation which does not represent enough the fine scale heterogeneities in reality. The heterogeneity which occurs in fuel, topography and weather is finer in reality than what was represented in the model. Fuel mapping in this study was based on the classification which had a Kappa coefficient of 0.83. The fine heterogeneity within the vegetation classes was therefore different from reality. The shrubs, for example, which were observed during fieldwork, could not be classified as a single class because of the incapability of identification on the satellite imagery.

Stopping the fire

Overestimation could also be attributed to the absence of detailed information concerning the suppression activities which were taken during the fire event. The fire simulated in the study stopped mainly due to the time duration indicated. In reality however fire stops due to changes in topography, fuel, weather and other barriers like roads and rivers (Arca et al., 2007). The model does not show this clearly. Whilst roads are important agents for fire ignition (Arca et al., 2006), they can also act as barriers to fire spread due to local absence of fuel. In this study they have acted as both agents for ignition and as barriers to spread in other parts of the study areas. The barriers used in this study are those which the researchers observed in the field. Field observations showed that some roads and valleys acted as barriers to the spread of fire. This was evident where one side of the road was burnt but the other was unburnt. Appendix 5 illustrates the parts of roads which acted as barriers to the spread of fire. This was in agreement with studies by other authors (LaCroix et al., 2006, Duncan and Schmalzer, 2004) who indicated the importance of barriers to minimize overestimation. Despite this adjustment, overestimation of the fire spread was however still observed.

The overestimation could also be attributed to the absence of fire suppression activities during the simulation process. This information was not provided during the time of the study. Although the model has a function for simulating ground and air suppression activities, these were not incorporated in this study. The detailed information related to the type of suppression activities taken during the fire was not provided as indicated in Appendix 7. Other studies (Arca et al., 2007, Arca et al., 2005, Arroyo et al., 2008, Ryu et al., 2007, LaCroix et al., 2006) in fire behaviour modelling have utilized fire suppression activities to stop the spread of fire. In these cases suppression was simulated according to the documented information about the fire. The study by (Arca et al., 2007) indicated in detail the location, timing and the type of fire suppression activities that were utilised in simulation of three fires which occurred in Mediterranean conditions in Italy. This helps in fine tuning the model simulations to get more accurate simulations.

It is however likely that the fire stopped due to the increasing presence of bare patches of land. This is evident in the Northern part of the study area (see Appendix 12) where the fire stops even in the absence of suppression activities and barriers. This observation is in agreement with the observation by (Ryu et al., 2007) where the fire is said to stop in the absence of fuel. Other factors such as topography and wind could have played a role in stopping the fire.

5.3. Simulation with spatially varying wind data

5.3.1. Spatially varying wind and unadjusted fuel model

The incorporation of spatially varying wind data proved to increase the rate of fire spread rate and hence allowing the fire scar to grow to the extent of the observed fire scar within the first 48 hours. The high agreement (95%) between the observed and simulated fire scars indicates that the incorporation of spatially varying wind data improves the ability of FARSITE to simulate fire area which better resembles the observed fire area. The extent of the fire agreed with the MODIS active dataset to a greater extent than without the adjustment of rate of fire spread because all the active fires detected by MODIS were included in the simulated fire scar. The simulated fire scar also follows the shape and pattern of growth as the observed fire scar. However higher overestimation occurred in the simulation which can be attributed to the factors highlighted in Section 5.2.2.

5.3.2. Spatially varying wind and adjusted fuel model

Although the adjustment of the rate of fire spread increased the level of agreement between the observed and the simulated fire scars the effect was low as shown in Figure 4-10. This could imply that the variation of wind has a larger effect on fire behaviour than fuel conditions. This agrees with the observation by (Bessie and Johnson, 1995) where they suggested that wind variation has more effect on fire behaviour than fuel. The average wind direction during the fire event was from the South and South-west. This is represented well by the shape of the simulated fire scar which shows fire spread in the same direction. The high temporal resolution in wind data could have contributed to the high similarity between the observed and simulated fire scars.

Wind direction fluctuations may change the shape of the fire spread, however only to the modelled spatial and temporal scale. In this study the wind was modelled at 30minute temporal resolution unlike the usual 1 hour (Arca et al., 2007, Arca et al., 2006, Arca et al., 2005) and daily (LaCroix et al., 2006) temporal resolutions. The generally high Sorensen's Coefficient (ranging from 0.64-0.84) in all the simulations indicates that there is a good agreement between the observed and the simulated fire scars. This agrees with the observations by Arca et al., 2007 who used Sorensen's Coefficient as an indicator of exclusive association between observed and simulated fire scars. Their values ranged between 0.62 and 0.72. The Kappa coefficients for the simulations also generally indicate high agreement between the simulated and observed fire scars.

The other possible explanations for overestimation and underestimation are similar to those highlighted in sections 5.2.1 and 5.2.2. The results in this study indicate that wind is an important factor in fire propagation. This agrees with other researchers (Arca et al., 2007, Duguy et al., 2007, Forthofer and Butler, 2007) who suggested that the use of uniform wind can underestimate fire behaviour. The simulation of the spatial variation in wind behaviour produces wind data that better represents reality that spatially uniform wind.

5.4. Spatial Distribution of fire intensity

The description of fires has been based on subjectively identifying them as ‘cool’ or ‘hot’(Keeley, 2008). It is therefore essential to quantify fire intensity. The intensity of fire is dependant on fuel, topography and weather (Finney, 1998, Finney, 2004, Andrews, 1986, Perry, 1998). The peak fireline intensity values were located in the pine plantations. This was evidenced by the charring of tree trunks and also the melting of the road sign post (see Appendix 10). The high intensity fire could be attributed to the fuel characteristics of conifers which are more susceptible (Cardille and Ventura, 2001, Ryu et al., 2007) to fire than most fuel types. The steep upslope could also have contributed to high fireline intensity. The distance between the flame and un-ignited fuel decreases as the fuel bed is tilted. When the fuel bed is tilted more radiative heat energy will reach the same fuel particle than on a level fuel bed.

In this study the spatial variation in fireline intensity was attributed mainly to the variation in fuel properties. The low fireline intensity in the beech forests could be attributed to the clearing of the forest floor by the park. This results in lower fuel load available for burning. The higher canopy cover in the beech forest also limits the amount of sunlight which reaches the forest floor to dry the leaf litter. Lower fireline intensity in the grass could be attributed to the physical characteristics of the grass. The observations in the mixed forest indicated that the intensity of the fire was low as shown by the absence of charring in Figure 3-12c. This agrees with the model simulations. The oak trees in the mixed forest were still standing and some of them showed no sign of burning. The lower intensity could be attributed to the presence of mixed tree species (Ryu et al., 2007) which provide fuel heterogeniety.

Fireline intensity is one of the important output parameters in FARSITE and depends rate of fire spread and heat per unit area (Andrews, 2009). Fireline intensity information may be useful when estimating the width of fire breaks which is useful to stop fires.

5.5. Identification of possible ignition point

A study by (LaCroix et al., 2006) reveals that the ignition location has the strongest/greatest influence on the spread of fire followed by other factors such as fuel and weather. In this study there was 90% similarity between the fire scars simulated using the suggested and the observed ignition points indicating a very high approximation of the simulation. This therefore shows that the model can be used to identify possible ignition points using provided information about the fire. This important function of the model can be utilised to confirm the given ignition point. This will be useful in cases where arson is involved and can help in the search for culprits. It is also important to highlight that the usefulness of the model for identifying possible ignition points depends on the reliability of the other data such as fuel, weather and topography.

5.6. Limitations of the Study

This study had some limitations as highlighted below.

Resampling

Although the resampling of the land cover map from spatial resolution of ALOS imagery (10m) to 30m could have resulted increased generalization (Hay et al., 1997, Wieczorek, 1992) of information the simulated fire scar corresponded well with the observed fire scar. This resampling usually known as upscaling was done to reduce the data size of the higher spatial resolution but maintaining the information at a lower spatial resolution (Hay et al., 1997). The spatial resolution of 30m was selected due to computational capabilities of the model and also based on other studies (Ryu et al., 2007) where similar resolution was used and realistic results were obtained. A study by (Gupta et al., 2000) indicated that the result from upscaling LISS-11 data of 36.25m to 72.5m resolution correlated with observed 72.5m resolution. Upscaling in this case managed to preserve maximum information (Gupta et al., 2000). Therefore although resampling could have generalized information we also assume that maximum information was preserved as indicated by the high agreement between the simulated and the observed fire scars. It is worth noting that the resampling in this study was done after the process of land cover classification and it was assumed that the effect was minimized.

Validation of Wind model

The validation of wind model requires ground measured data which were absent for the study area. However this model has been validated in other studies (Forthofer and Butler, 2007, Forthofer, 2007) hence its usefulness in this study was based on this validation. The model has been tested in complex terrain conditions which resemble conditions in this study. It is however not certain that the results from other conditions can be trusted under different conditions.

Suppression activities

This important effect of fire suppression activities was not therefore incorporated in the model simulations. This could have attributed to the overestimation of the model simulations.

Details on progress of the fire

In some studies (Arca et al., 2007) the details related to the progress of the fire have been provided. This is essential in simulating the fire event using fire models. Such information is useful when assessing the accuracy of the model in simulating reality. An example of such information include the time when the fire reached a given forest type. The insufficiency of such information could be attributed to either the absence of observations during the fire or the lack of documentation. This study reveals the importance of documenting all the information about a fire event.

Fuel Models

The fuel models applied in this study have been developed in the United States. Although the selected fuel models managed to give acceptable simulation results, they do not represent the conditions in the study area. The beech forest for example, is different from other beech forests in other regions (van Gils et al., 2010). Although the fuel model applied to this forest type closely resembles the conditions in Majella National Park, direct measurement of the parameters (SAV, heat per area, fuel load, fuel moisture) may result in more realistic fuel models. Most of the studies (LaCroix et al., 2006, Arca et al., 2007, Arroyo et al., 2008, Carmel et al., 2009, Duguy et al., 2007, Halada et al., 2006, Molina-Terrén et al., 2006) where fire simulation was involved in Mediterranean (Dimitrakopoulos, 2002, Dimitrakopoulos and Dritsa, 2003) conditions have developed custom fuel models. The fuel model parameters which were used in such studies were derived from intensive surveys where field measurements were made. However no such study has been done for montane conditions. It is therefore necessary to have such studies focussing on the development of fuel models specific for the montane conditions.

The fuel models assume that the fuel load within each cell is homogenous (Stephens, 1998), which is an oversimplification of the actual landscape because there are usually some small-scale differences in topography, canopy cover and fuels which affect the fire behaviour. This assumption was therefore incorporated into the fire model which assumed that the fire behavior (spread rate, intensity) was uniform within a given land cover type. This is not always real.

The choice of the fuel models was mainly based on the comparison between the description of the standard fuel models and the field observations. But it is possible that biomass in esp. the beech is different from that in the model, due also to the coppicing of the trees (van Gils et al., 2010).

6. Conclusions and Recommendations

6.1. Conclusions

The general conclusion of this study is that fire spread modelling using FARSITE (Finney, 1998) fire model can be applied well in montane condition. Based on the results and discussion the following specific conclusions were reached for each research question.

- **Does the simulated fire scar approximate the observed fire scar by at least 75%?**
  The fire scar simulated in FARSITE by the incorporation of uniform wind data had a similarity of 50% with the observed fire scar. The similarity between the simulated fire scar using uniform wind data failed to approximate the observed fire scar by at least 75%. The similarity between the fire scars however increases with the adjustment in wind and fuel model rate of spread. It is therefore concluded that the applicability of FARSITE in montane areas requires some adjustment. The agreement between the simulated and observed fire scar was at least 75% in all the other scenarios.

- **Does the incorporation of spatially varying wind information affect the approximation of the simulated fire scar to the observed fire scar?**
  The incorporation of spatially varying wind information increased the level of similarity between the simulated and observed fire scars. Therefore the incorporation of spatially varying wind information into the FARSITE model improves the similarity between simulated and observed fire scar as indicated by high values of Sorensen's and Kappa coefficients.

- **How is fireline intensity distributed within the simulated fire scar?**
  The simulation agrees well with the observed of fire intensity in the study area. In most parts of the scar except in the pine plantation fire intensity was generally low and this is also shown by the model simulation. Fireline intensity was highest in the pine forest. Field observations of charring on the pine trees also indicated a fire of high intensity.

- **Can fire modelling be useful in identifying the possible ignition points?**

This research question was forensic in trying to find out more about the possible single or multiple ignition points given conflicting information. In this study the simulation in FARSITE has indicated its usefulness in estimating the location of the possible ignition points. This was shown by the high (90%) similarity between the simulations using the ‘interpreted’ and the ‘true’ ignition points. The establishment of the most likely ignition point may be attributed to mainly the wind behaviour. The average southerly wind direction during the fire event is assumed to have attributed to the direction and shape of fire spread. Simulation with multiple ignition points produced unrealistic results. Hence the model can be used to help in investigating the origin of a fire.

6.2. Recommendations

Based on the results, discussion and conclusion in this study, the following recommendations have been made.

- Further research of actual fire behaviour in the field is necessary for the validation of the FARSITE model in the montane conditions.

- The wind data used in this study was acquired from a weather station outside the area where the fire occurred. It is recommended that a local weather station be set up to facilitate and improve the accuracy of research results.

- The accuracy of the modelling of spatially varying wind was not assessed because there was no field data collected for validation of the model. Further studies may involve the measurement of weather data for model validation (Forthofer and Butler, 2007, Forthofer et al., 2009, Forthofer, 2007, Ryu et al., 2007). There is therefore need for the comparison of simulated wind data with measured wind data to validate the wind model in the area.

- The incorporation of spatially varying wind data can be used for the identification of potentially high intensity wind driven wind behaviour

- In this study there was insufficient information about the fire event available. This may have affected the accuracy of the results.

- Due to the lack of information suppression activities were not incorporated in the fire spread modelling. This is an important process in fire modelling and therefore in further studies it is recommended that such information be incorporated.

- Forest management should be aimed at increasing fuel heterogeneity. Hence monospecific forest such as the pine and beech should be mixed other forest types. This could minimize the damage due to fire (Ryu et al., 2007, Stephens, 1998, van Gils et al., 2010).

- The fuel models used in this study were adopted from the ones developed in the United States. It is likely that these do not represent the fuel status in the study area well. Studies should therefore be focused on the mapping of the fuel characteristics in montane conditions. There is need for development of fuel models specifically for Europe because some of the species differ from the other vegetation species found in the other parts of the world.

- For management purposes, further studies should be dedicated to the mapping of fire risk areas in the national park using fire models.

- Further studies may simulate the spatial variation of wind speed and direction using a different wind model such as Wind Wizard (Forthofer, 2007) or WindStation (Lopes, 2003).

- It is also recommended that the FARSITE model incorporates the spatial variation within the single model.

- The use of adjustment factors in FARSITE is based on user decision. It is therefore recommended that specific adjustment factors be allocated for specific fuel models.

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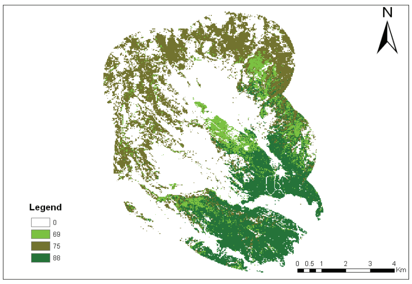
8. Appendices

Appendix 1: Canopy cover



Cover type	Mean Canopy cover	Standard deviation
Beech	88	3.12
Pine	69.29	3.15
Mixed forest	74.93	5.92
Open grass	93.4	4.73
Shrubs	31.14	9.91

Appendix 2: List of all fuel models (Source: Scott and Burgan, 2005)

Fuel model code	Fuel load (t/ac) 1-hr	10-hr	100-hr	Live herb	Live woody	Fuel model type[a]	SAV ratio (1/ft)[b] Dead 1-hr	Live herb	Live woody	Fuel bed depth (ft)	Dead fuel extinction moisture (percent)	Heat content BTU/lb)[c]
GR1	0.10	0.00	0.00	0.30	0.00	dynamic	2200	2000	9999	0.4	15	8000
GR2	0.10	0.00	0.00	1.00	0.00	dynamic	2000	1800	9999	1.0	15	8000
GR3	0.10	0.40	0.00	1.50	0.00	dynamic	1500	1300	9999	2.0	30	8000
GR4	0.25	0.00	0.00	1.90	0.00	dynamic	2000	1800	9999	2.0	15	8000
GR5	0.40	0.00	0.00	2.50	0.00	dynamic	1800	1600	9999	1.5	40	8000
GR6	0.10	0.00	0.00	3.40	0.00	dynamic	2200	2000	9999	1.5	40	9000
GR7	1.00	0.00	0.00	5.40	0.00	dynamic	2000	1800	9999	3.0	15	8000
GR8	0.50	1.00	0.00	7.30	0.00	dynamic	1500	1300	9999	4.0	30	8000
GR9	1.00	1.00	0.00	9.00	0.00	dynamic	1800	1600	9999	5.0	40	8000
GS1	0.20	0.00	0.00	0.50	0.65	dynamic	2000	1800	1800	0.9	15	8000
GS2	0.50	0.50	0.00	0.60	1.00	dynamic	2000	1800	1800	1.5	15	8000
GS3	0.30	0.25	0.00	1.45	1.25	dynamic	1800	1600	1600	1.8	40	8000
GS4	1.90	0.30	0.10	3.40	7.10	dynamic	1800	1600	1600	2.1	40	8000
SH1	0.25	0.25	0.00	0.15	1.30	dynamic	2000	1800	1600	1.0	15	8000
SH2	1.35	2.40	0.75	0.00	3.85	N/A	2000	9999	1600	1.0	15	8000
SH3	0.45	3.00	0.00	0.00	6.20	N/A	1600	9999	1400	2.4	40	8000
SH4	0.85	1.15	0.20	0.00	2.55	N/A	2000	1800	1600	3.0	30	8000
SH5	3.60	2.10	0.00	0.00	2.90	N/A	750	9999	1600	6.0	15	8000
SH6	2.90	1.45	0.00	0.00	1.40	N/A	750	9999	1600	2.0	30	8000
SH7	3.50	5.30	2.20	0.00	3.40	N/A	750	9999	1600	6.0	15	8000
SH8	2.05	3.40	0.85	0.00	4.35	N/A	750	9999	1600	3.0	40	8000
SH9	4.50	2.45	0.00	1.55	7.00	dynamic	750	1800	1500	4.4	40	8000
TU1	0.20	0.90	1.50	0.20	0.90	dynamic	2000	1800	1600	0.6	20	8000
TU2	0.95	1.80	1.25	0.00	0.20	N/A	2000	9999	1600	1.0	30	8000
TU3	1.10	0.15	0.25	0.65	1.10	dynamic	1800	1600	1400	1.3	30	8000
TU4	4.50	0.00	0.00	0.00	2.00	N/A	2300	9999	2000	0.5	12	8000
TU5	4.00	4.00	3.00	0.00	3.00	N/A	1500	9999	750	1.0	25	8000
TL1	1.00	2.20	3.60	0.00	0.00	N/A	2000	9999	9999	0.2	30	8000
TL2	1.40	2.30	2.20	0.00	0.00	N/A	2000	9999	9999	0.2	25	8000
TL3	0.50	2.20	2.80	0.00	0.00	N/A	2000	9999	9999	0.3	20	8000
TL4	0.50	1.50	4.20	0.00	0.00	N/A	2000	9999	9999	0.4	25	8000
TL5	1.15	2.50	4.40	0.00	0.00	N/A	2000	9999	1600	0.6	25	8000
TL6	2.40	1.20	1.20	0.00	0.00	N/A	2000	9999	9999	0.3	25	8000
TL7	0.30	1.40	8.10	0.00	0.00	N/A	2000	9999	9999	0.4	25	8000
TL8	5.80	1.40	1.10	0.00	0.00	N/A	1800	9999	9999	0.3	35	8000
TL9	6.65	3.30	4.15	0.00	0.00	N/A	1800	9999	1600	0.6	35	8000
SB1	1.50	3.00	11.00	0.00	0.00	N/A	2000	9999	9999	1.0	25	8000
SB2	4.50	4.25	4.00	0.00	0.00	N/A	2000	9999	9999	1.0	25	8000
SB3	5.50	2.75	3.00	0.00	0.00	N/A	2000	9999	9999	1.2	25	8000
SB4	5.25	3.50	5.25	0.00	0.00	N/A	2000	9999	9999	2.7	25	8000

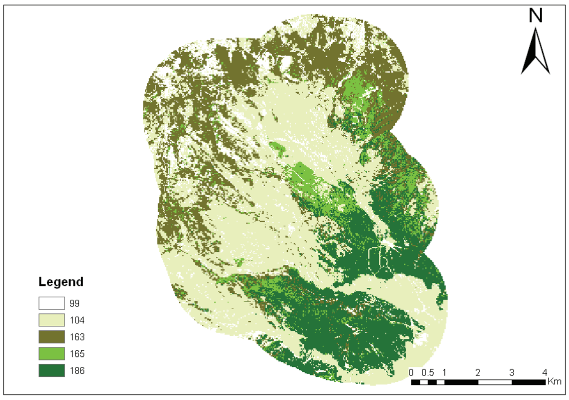
[a] Fuel model type does not apply to fuel models without live herbaceous load.
[b] The value 9999 was assigned in cases where there is no load in a particular fuel class or category
[c] The same heat content value was applied to both live and dead fuel categories.

Appendix 3: The numerical values of fuel characteristics used in the study

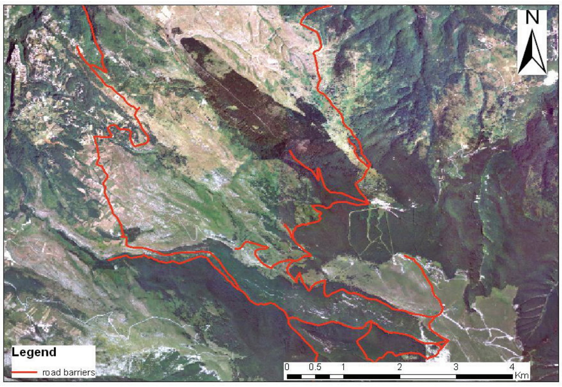
Fuel Model Code	**GR4**	**TL6**	**TU3**	**TU5**	**NB9**
Vegetation (fuel model)	Grass	Timber	Timber Understory	Timber understory	Bare ground
Observed Vegetation	Grass	Beech	Mixed forest	Pine	Bare
Fuel Load (ton/ ac)					N/A
1hr	0.25-0.56	2.40-5.45	1.10-2.5	4.00-9.09	
10hr	0.00	1.20-2.73	0.15-0.34	4.00-9.09	
100hr	0.00	1.20- 2.73	0.25-0.56	3.00-6.82	
Live herbaceous	1.90-4.32	0.00	0.65-1.48	0.00	
Live woody	0.00	0.00	1.10-2.5	3.00-6.82	
Fuel model type	dynamic	N/A	dynamic	N/A	N/A
SAV ratio (1/ft)					N/A
1-hr	2000	2000	1800	1500	
Live Herbaceous	1800	9999	1600	9999	
Live woody	9999	9999	1400	750	
Fuel bed depth (ft)	2.0-60	0.3-9.14	1.3-39.62	1.0-30.48	N/A
Dead fuel extinction Moisture (%)	15	25	30	25	N/A

Adopted from (Arca et al., 2006, Scott and Burgan, 2005)

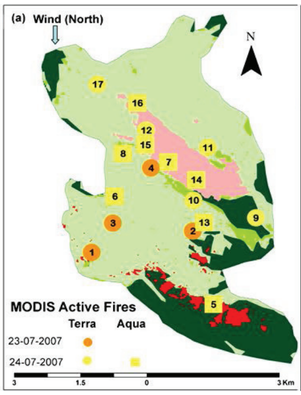
Appendix 4: Fuel model map



Appendix 5: Roads as barriers to fire spread



Appendix 6: MODIS active fire data

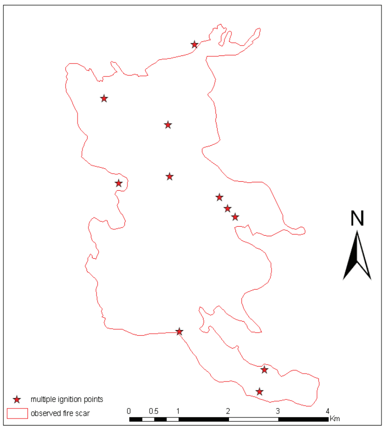


Number	Acquisition date	Satellite	Time (UTC[a])	Location (projected coordinates) X	Y	Brightness[b] temperature (K)	Detection confidence (%)	FRP[c] ($W m^{-2}$)
1	23-07-2007	Terra	2050	421698.342	4670793.152	317	91	18
2	23-07-2007	Terra	2050	423975.691	4671310.731	309	55	11
3	23-07-2007	Terra	2050	422201.133	4671502.975	329	96	41
4	23-07-2007	Terra	2050	423058.836	4672774.741	319	74	24
5	24-07-2007	Aqua	0100	424448.906	4669565.749	315	88	17
6	24-07-2007	Aqua	0100	422230.709	4672138.858	332	100	37
7	24-07-2007	Aqua	0100	423443.323	4672907.833	318	95	17
8	24-07-2007	Aqua	0100	422408.165	4673114.865	325	100	26
9	24-07-2007	Terra	1025	425454.489	4671636.066	367	100	215
10	24-07-2007	Terra	1025	424005.267	4672020.554	399	100	504
11	24-07-2007	Terra	1025	424345.390	4673233.168	372	100	250
12	24-07-2007	Terra	1025	422940.532	4673662.020	375	100	268
13	24-07-2007	Aqua	1205	424256.662	4671502.975	340	80	37
14	24-07-2007	Aqua	1205	424079.207	4672508.557	341	79	38
15	24-07-2007	Aqua	1205	422925.744	4673321.896	351	96	53
16	24-07-2007	Aqua	1205	422733.500	4674297.903	394	100	206
17	24-07-2007	Terra	2135	421831.433	4674726.755	317	91	48

[a] UTC: Universal Time; a.k.a. Greenwich Mean Time (GMT).
[b] Brightness temperature (channel 22).
[c] FRP: fire radiative power.

Source : van Gils (2010)

Appendix 7: Some of the multiple ignition points tested in the simulation



Appendix 8: Fire Details (SOURCE: Giampiero Ciaschetti (park personnel))

Question: When and where was the first fire detected?

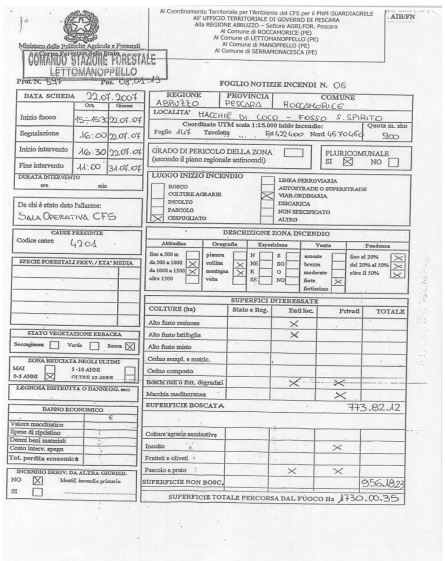
Response: It was detected on Sunday 22nd at 3:00 – 3:30 p.m. at the right side of the road to La Majelletta, right after the junction with the road to the St. Spirito hermitage.

Question: What type of fire suppression activities was taken? Where was the fire suppression activities done?

Response: We asked the Forestry Police because they have more detailed data then us. I will send those data t0 you soon when I will have them.

Question: How long did the fire event last?

Response: the fire event went on from Sunday 22nd (first detection), and below the leaf litter was not over before one month - it was completely extinguished on Tuesday 31st



Al Coordinamento Territoriale per l'Ambiente del CFS per il PNM GUARDIAGRELE
All' UFFICIO TERRITORIALE DI GOVERNO DI PESCARA
Alla REGIONE ABRUZZO – Settore AGRI.FOR. Pescara
Al Comune di ROCCAMORICE (PE)
Al Comune di LETTOMANOPPELLO (PE)
Al Comune di MANOPPELLO (PE)
Al Comune di SERRAMONACESCA (PE)

AIB/FN

Ministero delle Politiche Agricole e Forestali
Corpo Forestale dello Stato
COMANDO STAZIONE FORESTALE LETTOMANOPPELLO
Prot. N. 597 Pos. 08.01.13

FOGLIO NOTIZIE INCENDI N. 06

DATA SCHEDA	22.07.2007	
	Ora	Giorno
Inizio fuoco	15÷15:30	22.07.07
Segnalazione	16:00	22.07.07
Inizio intervento	16:30	22.07.07
Fine intervento	11:00	31.07.07
DURATA INTERVENTO	ore	min

REGIONE	PROVINCIA	COMUNE
ABRUZZO	PESCARA	ROCCAMORICE

LOCALITA' MACCHIE DI COCO - FOSSO S. SPIRITO

Coordinate UTM scala 1:25.000 inizio incendio: Foglio 147 Tavoletta ... Est 422400 Nord 4670460 Quota m. slm 900

GRADO DI PERICOLO DELLA ZONA (secondo il piano regionale antincendi) ☐

PLURICOMUNALE SI ☒ NO ☐

LUOGO INIZIO INCENDIO: ☐ BOSCO ☐ COLTURE AGRARIE ☐ INCOLTO ☐ PASCOLO ☒ CESPUGLIATO ☐ LINEA FERROVIARIA ☐ AUTOSTRADE O SUPERSTRADE ☒ VIAB.ORDINARIA ☐ DISCARICA ☐ NON SPECIFICATO ☐ ALTRO

Da chi è stato dato l'allarme: SALA OPERATIVA CFS

CAUSE PRESUNTE: Codice causa 4201

SPECIE FORESTALI PREV. / ETA' MEDIA

DESCRIZIONE ZONA INCENDIO

Altitudine	Orografia	Esposizione	Vento	Pendenza
☐ fino a 500 m	☐ pianura	☐ N ☐ S	☐ assente	☒ fino al 20%
☒ da 500 a 1000	☒ collina	☐ NE ☐ SO	☐ brezza	☒ dal 20% al 50%
☒ da 1000 a 1500	☒ montagna	☐ E ☐ O	☐ moderato	☒ oltre il 50%
☐ oltre 1500	☐ vetta	☐ SE ☐ NO	☒ forte	
			☐ fortissimo	

STATO VEGETAZIONE ERBACEA: Seccaginosa ☐ Verde ☐ Secca ☒

ZONA BRUCIATA NEGLI ULTIMI: MAI ☐ 0-5 ANNI ☒ 5-10 ANNI ☐ OLTRE 10 ANNI ☐

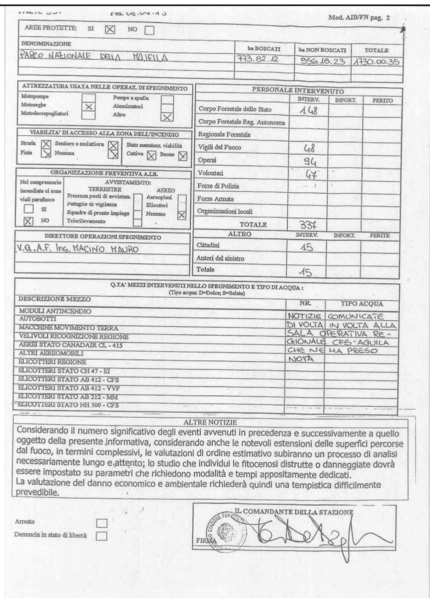
LEGNOSA DISTRUTTA O DANNEGG. mc:

SUPERFICI INTERESSATE

COLTURE (ha)	Stato e Reg.	Enti loc.	Privati	TOTALE
Alto fusto resinose		X		
Alto fusto latifoglie		X		
Alto fusto misto				
Ceduo sempl. e matric.				
Ceduo composto				
Boschi radi o fort. degradati		X	X	
Macchia mediterranea			X	
SUPERFICIE BOSCATA				773.82.12
Colture agrarie seminative				
Incolto			X	
Frutteti e oliveti				
Pascolo e prato		X	X	
SUPERFICIE NON BOSC.				956.18.23
SUPERFICIE TOTALE PERCORSA DAL FUOCO Ha				1730.00.35

DANNO ECONOMICO	€
Valore macchiatico	
Spese di ripristino	
Danni beni materiali	
Costo interv. spegn	
Tot. perdita economica	

INCENDIO DERIV. DA ALTRA GIURISD.: NO ☒ SI ☐ Identif. incendio primario



Mod. AIB/FN pag. 2

AREE PROTETTE: SI ☒ NO ☐

DENOMINAZIONE	ha BOSCATI	ha NON BOSCATI	TOTALE
PARCO NAZIONALE DELLA MAJELLA	773.82.12	956.18.23	1730.00.35

ATTREZZATURA USATA NELLE OPERAZ. DI SPEGNIMENTO: Motopompe ☐ Motoseghe ☒ Motodecespugliatori ☐ Pompe a spalla ☐ Atomizzatori ☐ Altro ☒

VIABILITA' DI ACCESSO ALLA ZONA DELL'INCENDIO: Strada ☒ Pista ☒ Sentiero o mulattiera ☒ Nessuna ☒ Stato manutenz. viabilità: Cattivo ☒ Buono ☒

ORGANIZZAZIONE PREVENTIVA A.I.B.: Nel comprensorio incendiato ci sono viali parafuoco ☐ SI ☒ NO. AVVISTAMENTO: TERRESTRE: Presenza posti di avvistam. ☐ Pattuglie di vigilanza ☐ Squadre di pronto impiego ☐ Telerilevamento ☐ AEREO: Aereoplani ☐ Elicotteri ☐ Nessuno ☒

DIRETTORE OPERAZIONI SPEGNIMENTO: V.Q.A.F. Ing. MACINO MAURO

PERSONALE INTERVENUTO	INTERV.	INFORT.	PERITO
Corpo Forestale dello Stato	148		
Corpo Forestale Reg. Autonoma			
Regionale Forestale			
Vigili del Fuoco	48		
Operai	94		
Volontari	47		
Forze di Polizia			
Forze Armate			
Organizzazioni locali			
TOTALE	337		

ALTRO	INTERV.	INFORT.	PERITE
Cittadini	15		
Autori del sinistro			
Totale	15		

Q.TA' MEZZI INTERVENUTI NELLO SPEGNIMENTO E TIPO DI ACQUA: (Tipo acqua: D=Dolce; S=Salata)

DESCRIZIONE MEZZO	NR.	TIPO ACQUA
MODULI ANTINCENDIO		
AUTOBOTTI	NOTIZIE	COMUNICATE
MACCHINE MOVIMENTO TERRA	DI VOLTA	IN VOLTA ALLA
VELIVOLI RICOGNIZIONE REGIONE	SALA O	PERATIVA RE-
AEREI STATO CANADAIR CL - 415	GIONALE	CFS - AQUILA
ALTRI AEREOMOBILI	CHE NE	HA PRESO
ELICOTTERI REGIONE	NOTA	
ELICOTTERI STATO CH 47 - EI		
ELICOTTERI STATO AB 412 - CFS		
ELICOTTERI STATO AB 412 - VVF		
ELICOTTERI STATO AB 212 - MM		
ELICOTTERI STATO NH 500 - CFS		

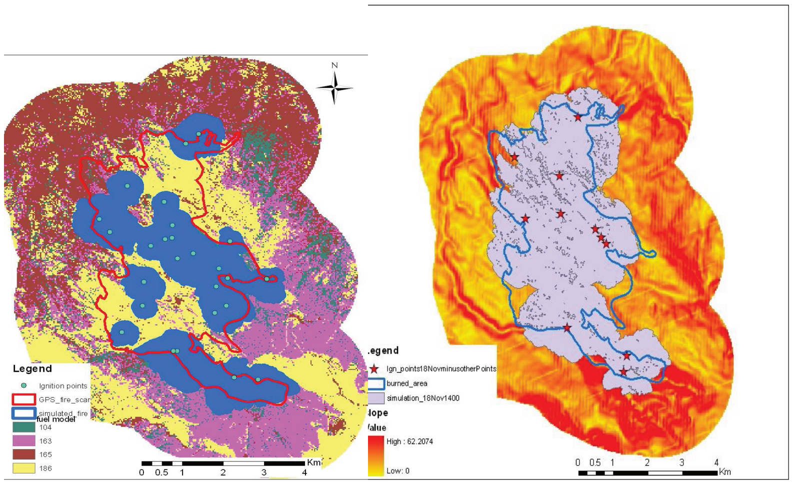
ALTRE NOTIZIE

Considerando il numero significativo degli eventi avvenuti in precedenza e successivamente a quello oggetto della presente informativa, considerando anche le notevoli estensioni delle superfici percorse dal fuoco, in termini complessivi, le valutazioni di ordine estimativo subiranno un processo di analisi necessariamente lungo e attento; lo studio che individui le fitocenosi distrutte o danneggiate dovrà essere impostato su parametri che richiedono modalità e tempi appositamente dedicati.
La valutazione del danno economico e ambientale richiederà quindi una tempistica difficilmente prevedibile.

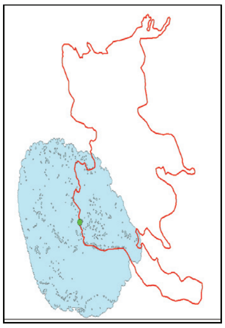
Arresto ☐
Denuncia in stato di libertà ☐

IL COMANDANTE DELLA STAZIONE
FIRMA

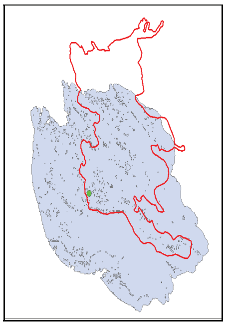
Appendix 9: Simulations using multiple ignition points



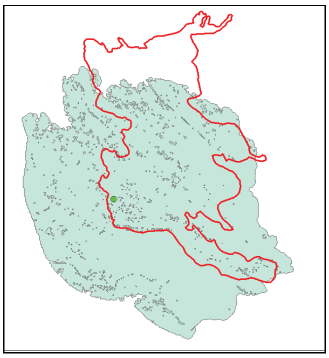
Appendix 10: Simulations with adjusting the location of ignition points



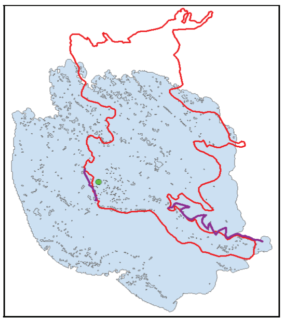
Ignition point at the edge of the scar



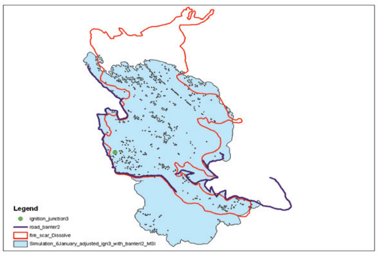
Adjusted ignition point



Adjusted ignition (2)



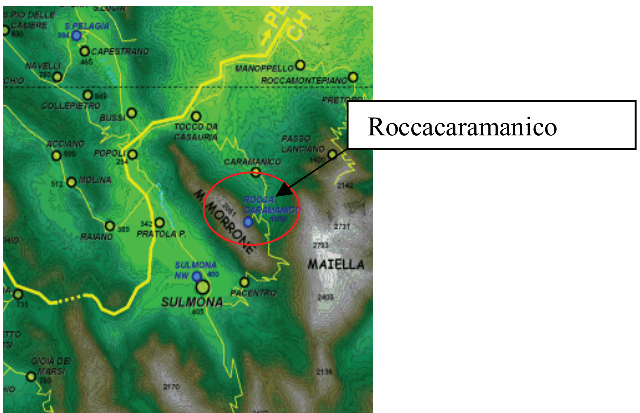
Adjusted ignition plus barrier



Adjusted ignition plus longer road barrier

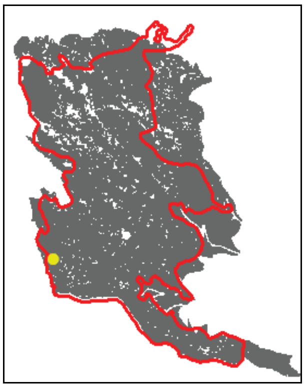
Appendix 10: Burnt road sign post

Appendix 11: Locations of the weather stations near Majella National Park.

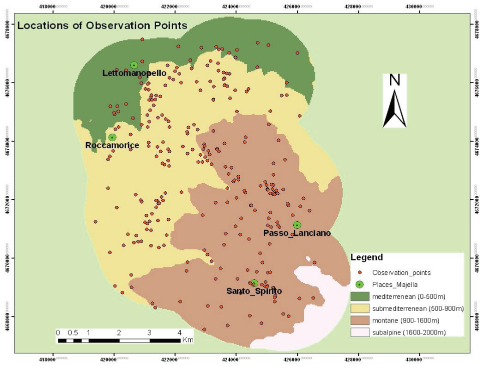


Yellow locations indicate the non-functional weather station whilst the blue locations are the functional weather stations

Appendix 12: Map showing increase in bare areas to the North of the fire scar



Appendix 13: Location of field observation points



Appendix 14: Ground observation coordinates (UTM) in the study area

X	Y	cover_type	condition
426201	4672047	beech	unburnt
425224	4672227	beech	unburnt
425253	4672186	beech	unburnt
425536	4672352	beech	unburnt
424954	4669047	beech	unburnt
425027	4669052	beech	unburnt
425217	4668990	beech	unburnt
424847	4669108	beech	unburnt
425038	4669508	beech	burnt
424575	4669120	beech	burnt
424455	4669158	beech	burnt
421345	4668318	beech	unburnt
424466	4669141	beech	burnt
424153	4668810	beech	burnt
424452	4668043	beech	unburnt
423502	4669664	beech	unburnt
423198	4669907	beech	burnt
424671	4669547	beech	burnt
424376	4669597	beech	burnt
425111	4669518	beech	burnt
425010	4669027	beech	unburnt
425201	4668989	beech	unburnt
422374	4669568	beech	unburnt
424420	4670655	beech	unburnt
425536	4672352	beech	unburnt
425101	4670496	beech	unburnt
426100	4671781	beech	unburnt
423982	4671102	beech	burnt
423516	4668343	beech	unburnt
425280	4668718	beech	unburnt
423058	4670135	beech	burnt
423328	4669299	beech	unburnt
425110	4671563	beech	unburnt
426065	4668632	beech	unburnt
424452	4668044	beech	unburnt
425273	4668534	beech	unburnt
425533	4668110	beech	unburnt

X	Y	cover_type	condition
425268	4668658	beech	unburnt
424963	4669192	beech	burnt
424377	4669597	beech	unburnt
422409	4669879	beech	unburnt
424153	4668810	beech	unburnt
424785	4670182	beech	unburnt
424042	4669293	beech	unburnt
425064	4671377	beech	unburnt
426520	4668651	beech	unburnt
422956	4670282	beech	burnt
426201	4672047	beech	unburnt
425721	4668021	beech	unburnt
426402	4671632	beech	unburnt
425843	4670818	beech	unburnt
424834	4667786	beech	unburnt
422950	4667574	beech	unburnt
423727	4667706	beech	unburnt
423668	4670835	beech	unburnt
X	**Y**	**cover_type**	**condition**
420581	4669007	mixed forest	unburnt
420581	4669007	mixed forest	unburnt
422950	4667574	mixed forest	unburnt
424834	4667786	mixed forest	unburnt
420271	4668829	mixed forest	unburnt
421136	4673839	mixed forest	burnt
421396	4673481	mixed forest	burnt
420395	4675279	mixed forest	burnt
420920	4677476	mixed forest	unburnt
420927	4676725	mixed forest	unburnt
420098	4676442	mixed forest	unburnt
420400	4676422	mixed forest	unburnt
420845	4676185	mixed forest	unburnt
420902	4675981	mixed forest	unburnt
421136	4676334	mixed forest	unburnt
421130	4676319	mixed forest	unburnt
421759	4676583	mixed forest	unburnt
422108	4677241	mixed forest	unburnt
422061	4676514	mixed forest	unburnt

422001	4676400	mixed forest	unburnt
422139	4676300	mixed forest	unburnt
421947	4676107	mixed forest	unburnt
421826	4676172	mixed forest	unburnt
422193	4676002	mixed forest	unburnt
421680	4675912	mixed forest	unburnt
422547	4676485	mixed forest	unburnt
422501	4676770	mixed forest	unburnt
421138	4675987	mixed forest	unburnt
421145	4675763	mixed forest	unburnt
421161	4675416	mixed forest	unburnt
421136	4673839	mixed forest	burnt
421396	4673481	mixed forest	unburnt
421594	4673244	open grass	burnt
421740	467316	mixed forest	burnt
420544	4673716	mixed forest	unburnt
421811	4673159	mixed forest	burnt
421660	4673203	mixed forest	burnt
420553	4674236	mixed forest	unburnt
420048	4674404	mixed forest	unburnt
420151	4674491	mixed forest	unburnt
420140	4675010	mixed forest	unburnt
419814	4673378	mixed forest	unburnt
419866	4673485	mixed forest	unburnt
425665	4676002	mixed forest	unburnt
425493	4675566	mixed forest	unburnt
425660	4675578	mixed forest	unburnt
426087	4674862	mixed forest	unburnt
425115	4675024	mixed forest	unburnt
425064	4674576	mixed forest	unburnt
422862	4677201	mixed forest	unburnt
423054	4676591	mixed forest	unburnt
423425	4676413	mixed forest	unburnt
423403	4676660	mixed forest	unburnt
423166	4676743	mixed forest	unburnt
420792	4670562	mixed forest	unburnt
425854	4671481	open grass	unburnt
422405	4674266	open grass	burnt
422388	4674319	open grass	surroundings

			burnt
422628	4674558	open grass	burnt
422260	4673821	open grass	burnt
422435	4674471	open grass	burnt
421388	4671756	open grass	burnt
421463	4671874	open grass	burnt
421424	4671956	open grass	burnt
421562	4672097	open grass	burnt
421611	4671972	open grass	burnt
421248	4671517	open grass	burnt
421434	4671290	open grass	burnt
421165	4671263	open grass	unburnt
421024	4671240	open grass	unburnt
421099	4671193	open grass	unburnt
421072	4670992	open grass	burnt
421213	4670956	open grass	unburnt
420889	4671993	open grass	unburnt
420919	4671931	open grass	unburnt
421254	4668473	open grass	unburnt
423077	4668375	open grass	unburnt
421594	4673244	open grass	burnt
421511	4675533	open grass	burnt
421781	4673340	open grass	burnt
422747	4674390	open grass	burnt
423259	4674356	open grass	burnt
424288	4673967	open grass	unburnt
424310	4674139	open grass	unburnt
424129	4670813	open grass	burnt
423328	4671900	open grass	burnt
423611	4670463	open grass	unburnt
421783	4671333	open grass	burnt
424024	4675022	open grass	unburnt
420656	4670546	open grass	unburnt
421638	4670442	open grass	burnt
421724	4670796	open grass	burnt
423254	4675417	open grass	burnt
424861	4669856	open grass	unburnt
424947	4672610	open grass	burnt

425594	4673368	open grass	unburnt
422906	4671471	open grass	burnt
421690	4672236	open grass	burnt
425222	4673249	open grass	unburnt
422574	4673722	open grass	burnt
423668	4670835	beech	unburnt
424161	4671376	open grass	burnt
425855	4671481	open grass	unburnt
421374	4671980	open grass	unburnt
426567	4669853	open grass	unburnt
422212	4672261	open grass	unburnt
423711	4671920	open grass	unburnt
421468	4670365	open grass	unburnt
423613	4673923	open grass	unburnt
421484	4671882	open grass	unburnt
423351	4677220	open grass	unburnt
423253	4675416	open grass	burnt
424024	4675022	open grass	unburnt
421345	4668318	open grass	unburnt
425388	4674035	open grass	unburnt
422172	4668530	open grass	unburnt
420564	4669441	open grass	unburnt
420716	4672171	open grass	unburnt
419863	4670205	open grass	unburnt
419393	4671251	open grass	unburnt
420315	4670444	open grass	unburnt
420792	4670562	mixed forest	unburnt
420465	4670827	open grass	unburnt
419808	4672397	open grass	unburnt
419967	4673668	open grass	unburnt