Fire behaviour of the large fires of 2007 in Greece

Miltiadis Athanasiou
"Environmental Impact Assessment Studies"
8 Thoma Paleologou st., 13673 Acharnes, info@m-athanasiou.gr
Gavriil Xanthopoulos
National Agricultural Research Foundation, Greece,
Institute of Mediterranean Forest Ecosystems & Forest Products Technology
Hymettus Avenue & 1 N. Chlorou st., 11528 Athens, gxnrtc@fria.gr

---

Abstract

The large wildfires of the fire season of 2007 in Greece that left approximately 270,000 ha burned and 78 people dead, presented a clear case of extreme fire behavior. This behavior is described in brief here. Furthermore, in the context of a fire modeling study, twelve of these fires were documented in detail and their behaviour was studied.

Fire behaviour observations were matched with observations and measurements of weather, topography and forest fuels that were recorded at the time of the fire. Additional complimentary information was gathered after the fires were controlled. Subsequently, detailed case studies were generated for each of the documented fires providing data that were then used for the development of a reliable database of fire behaviour observations.

A subset of this database was used to test fire behaviour predictions from the BehavePlus fire behaviour prediction system versus field observations for fuel situations corresponding to a fuel model for "evergreen-schlerophyllous shrublands (maquis) (1.5 - 3 m)" that had been developed, earlier for Greece. The results were positive, showing good agreement between observations and predictions, leading to the conclusion that, at least this fuel model can be used reliably for surface fire behaviour prediction for this fuel type in Greece. Additional investigations led to positive preliminary results in regard to the possibility to predict active crown fire behaviour in Pinus halepensis forests based on surface fire behaviour predictions obtained from BehavePlus and the shrub fuel model above as input.

Keywords: Wildfire behaviour prediction, fuel model, shrub fuels, wildfire management, Greece

1. Introduction

The fire season of 2007 in Greece was the worst in recent history. More than 270,000 ha burned, 110 villages were affected directly by the fire fronts and more than 3000 homes were totally or partially destroyed. Most important, a total of seventy eight (78) people, mostly civilians, lost their lives in a series of fire related accidents (Xanthopoulos et al. 2009). Whereas certain operational firefighting weaknesses may be partially responsible for the huge disaster, it is the extreme fire behavior of many of the fires of that summer that explains why the firefighting mechanism reached, at times, the point of total collapse. The work presented here, provides a brief description of that fire season and the type of fire behavior that the firefighters had to face, based to a large extent on the fire documentation efforts of the first author in the context of a fire behavior modelling study. Part of the results of the study as related to the behavior of the fires of 2007, are presented here as well.

2. The behaviour of the large fires of 2007 in Greece

Signs about the difficulty of the fire season of 2007 were evident early on. Snowfall in winter was deficient, even on high mountain slopes, making it impossible for many ski areas to operate. Rainfall was also well below normal. In response to the signs, the government increased the firefighting capacity of the country by contracting more heavy lift helicopters.

In the last ten days of June a heat wave with temperatures exceeding 40 ^{o}C in many parts of the country contributed to an early start of the “main” fire season. It started with two large fires in middle Greece, one of them claiming two civilian lives in the evening of June 27 near the village Agia on mount Ossa. At about the same time, at 19:30 on June 27, the fire of mount Parnis, started. Mount Parnis forms the NW part of the basin in which the city of Athens is built and is a National Park. The cause of the fire was sparks from an overloaded power line near the village of Stefani in the prefecture of Viotia, 15 km to the west of the mountain. Initial attack failed as aerial resources had little time to act before sunset and ground forces proved ineffective. In the six hours between 23:30 of 27/6/2007 and 05:30 of 28/6/2007, the fire front spread over a distance of approximately 2,2 km (rate of spread 0.36 km/h) burning mainly shrubs or Aleppo pine (Pinus halepensis) forest with evergreen shrub understory.

In the morning of June 28, increased firefighting efforts, mainly from the air, nearly achieved control by 10:00. However, some judgement errors in firefighting allowed the fire to continue. On-site weather measurements around 12:30 indicated that the temperature was 34 ^{o}C, the relative humidity was 31% and the wind was blowing from various directions with a mean wind speed of 27 km/h and gusts up to 57 km/h. In the 7 hours and 15 minutes between 06:45 and 14:00 hours, the fire front spread over a distance of 4 km, exhibiting an average rate of spread of 0.55 km/h. At 16:50 the fire front crossed without strong resistance the last road and firebreak intended to protect mount Parnis from a fire approaching from the west. After that the fire started moving into the core of the Park in three separate uphill runs, passing from the Aleppo pine forest to the fir (*Abies cephallonica*) forest at the top of the mountain. It accelerated as the slope increased and developed a strong convection column. The main run was in a SE direction, in a long draw between two peaks. Average fire spread during this run was estimated at 4.5 km/h with a peak spread of 6.6 km/h. The wind was from the west, measured at 9,4 km/h at this time with gusts up to 17 km/h. Relative humidity was at 31% and temperature was at 31 ^{o}C. However, channelling effects in the draw may have increased the local wind speed significantly. After reaching the rim of the mountain facing Athens at about 23:00 the fire calmed down. It was controlled in the next morning as it was moving slowly downslope without wind. The total burned area reached 5,600 ha, including 2,180 ha of fir forest.

A second heat wave hit the country between July 17 and 26, and with it came the second round of disaster. Numerous fires erupted and among them many escaped initial attack and grew to large sizes. The most notable was a fire that started on the 24th of July at Kounina, a village at the base of the steep mountains in the area of Aigialia (near the city of Aigio on the north coast of Peloponnese). Initial attack from the air was delayed as there were other fires in progress. On the 25th of July, with the help of the slope and a strong wind, it accelerated and burned, practically unobstructed, through the forests, agricultural cultivations and villages on the slopes of the mountains, until it reached the top. Within the next three days it burned about 30,000 ha, destroyed more than 70 homes in nine villages and killed three citizens. Most notably, and due to the drought, in addition to all the fast spreading fires in southern Greece, a series of fires in the high elevation and low flammability forests of northern Greece, started from various causes. Fought poorly they became surprisingly large. They kept burning for more than ten days until, on August 5, that part of Greece received a significant quantity of rain.

The fires in southern Greece continued in August with fire behaviour worsening as the vegetation was becoming more water stressed. On August 16 the people of Athens watched the fire of Penteli mountain which is opposite mount Parnis forming the NE part of the basin of Athens. The fire started at about 10:15. The temperature at 11:11 was 30 ^{o}C, relative humidity was 33% and the wind blew from the NE varying, according to the measurements of meteorological stations in the area, between 13 km/h and 26 km/h. Initial attack errors allowed the fire to grow in the young Aleppo pine forest and Mediterranean shrub fields that had regenerated after previous fires. Soon, with the help of an unstable atmospheric profile, a strong convection column was formed which created strong local indrafts near the fire perimeter. The aerial resources that arrived at this “plume dominated fire” (Rothermel 1991) by 11:00 were not able to make drops near the front due to the strong turbulence. Later, at about 12:30 the wind increased to 35 km/h the fire became wind driven and the strong fleet of Canadair waterbombers and heavy lift helicopters (Erickson S-64, MIL MI-26) started drops that helped control the fire by late evening. The burned area reached 900 ha. The maximum rate of spread of the fire, while it run unobstructed, was measured up to 2.5 km/h in Aleppo pine stands with shrub understory. The overall spread of the fire from 10:30 to 12:30, burning mainly Mediterranean shrub and young Aleppo pine regeneration, was calculated at 1.2 km/h.

Intense fires continued in the following days stressing the demoralized firefighting mechanism to the limit. Then, on 21st of August, the third heat wave of the summer arrived bringing the temperature up to more than 39 degrees Celsius for the next three days preheating and drying the fuels. Two fires on mount Parnon and mount Taygetus in Peloponnese that started on Thursday, August 23, were allowed to burn overnight. On August 24 relative humidity dropped to extremely low levels (8-20%) and wind picked-up, in many cases, exceeding 25-30 km/h with gusts reaching 50 km/h or more, bringing fire danger to extreme levels. When fires, starting in this explosive situation, were faced with ineffective initial attack, the stage was set for disaster.

In the morning of Friday 24th the fires of mount Parnon and Taygetus started raging out of control. A new fire erupted near the towns of Oitylo & Areopolis, roughly 30 km south of the fire of Taygetos. Within a few hours it caused six deaths. It attracted immediately the attention of the firefighters and the media until, in the afternoon, the news about massive fatalities in Ilia (western Peloponnese) started coming. Twenty three people near the village of Artemida were surrounded by a fire that was spreading in a mix of olive groves and clubs of Aleppo pine trees. They were trapped between the main fire front, which was spreading at a rate exceeding 5 km/h and spot fires that were produced massively by the falling burning embers from the huge convection column and were drawn back towards the column by strong indrafts (Xanthopoulos et al. 2009). Additionally, the rate of spread of some bursts was measured from 7 km/h up to 10 km/h (Athanasiou, 2008).

Four more fires with similar extreme behavior were added within the next few hours in Peloponnese. Furthermore, two major fires erupted on Evia island while the area around

Athens also received its share of fire activity. For three days, firefighting collapsed almost completely in spite of significant firefighting help received from abroad. Sixty seven (67) people died due to these fires. Most of the dead were caught in the open. They were trying to flee or were surrounded by the fire while trying to save their property. Added to the eleven (11) people who had died earlier they add-up to seventy eight (78) dead during the fire season, a death toll exceeding by far anything the country had experienced in the past.

Figure 1: The fires in south Greece, growing rapidly on the 25th of August (NASA image, captured by the MODIS aqua sensor).

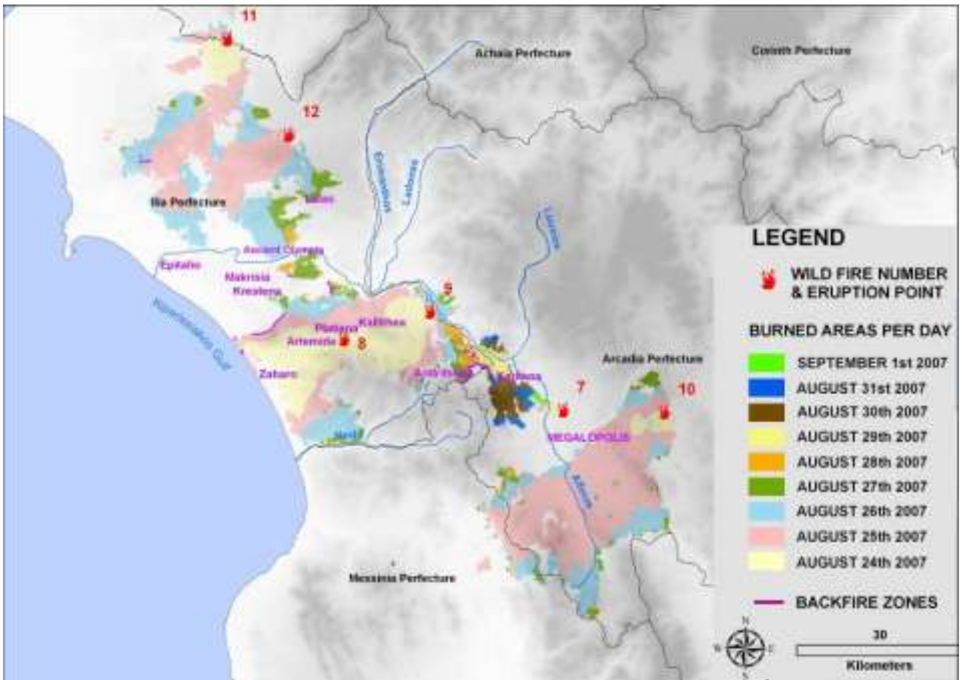

Figure 2: Evolution of the fires in central-west Peloponnese (August 24th to September 1st).

3. Fire behaviour modelling study

Fire behaviour prediction systems play an important role in modern forest fire management. The core of such systems is the fire behaviour model on which they are based. During the last forty years, many such models have been developed for predicting rate of spread, flame length, fire line intensity, etc.

Fire behaviour models can be adopted in wildfire management (forest management, fire prevention and suppression) only if their degree of reliability, strengths and weaknesses are well known. Preliminary evaluation can be performed in laboratory burns and in low intensity fires in the open but full confidence can only be achieved if model predictions are tested against observations of the behaviour of large wildfires.

Rothermel's mathematical model (1972) for predicting fire spread in wildland fuels is probably the most widely used model of this kind in the world. The popularity it enjoys is due mainly to its practicality, good documentation and a significant number of studies that tested its prediction performance for various types of fuels. Due to this extensive testing both strengths and weaknesses are quite well known. However, much of this testing has taken place in the laboratory, in experimental field burns or in actual wildfires of low to medium intensity (Van Wilgen et al., 1985, Xanthopoulos, 1986, McAlpine and Xanthopoulos, 1989). The extreme wildfires of 2007 in Greece provided an opportunity for model testing on fires spreading under extreme conditions in some important fuel complexes found in the country. More specifically, the current work, focused on documenting fire behaviour in the summer of 2007, and then testing the capacity of the BehavePlus fire behaviour prediction system (Andrews et al., 2005) which is based on Rothermel's (1972) model, to predict that behaviour.

4. Methodology

Twelve wildfires were documented in the regions of Attica, Viotia, Corinthia, Achaia, Ilia, Arcadia and Messinia, from June to September 2007; overall, 12,500 km were travelled and 750 hours of fieldwork were spent (Athanasiou, 2008).

Table 1: The twelve documented forest fires of 2007

	Wildfire name	Fire eruption (time – date)	Number of days fire spread	Burned area estimate (ha)
1	Stefani (Viotia Perfecture) - Parnis mountain (Attica)	19:30 - 27/06/2007	3	**5045**
2	Hymettus mountain (Attica)	14:50 - 16/07/2007	<1	**41**
3	Ancient Corinth (Corinth Perfecture)	16:00 - 17/07/2007	<1	**1605**
4	Chiliomodi (Corinth Perfecture)	14:30 - 18/07/2007	2	
5	Egialia (Achaia Perfecture)	21:30 - 23/07/2007	5	**14306**
6	Pedeli mountain (Attica)	10:30 - 16/08/2007	<1	**950**
7	Soulos (Arcadia Perfecture)	12:20 - 24/08/2007	3	**44841**
8	Paleochori (Ilia Perfecture)	14:35 - 24/08/2007	5	
9	Sekoulas (Ilia Perfecture)	14:30 - 24/08/2007	9	
10	Doriza (Arcadia Perfecture)	23:00 - 24/08/2007	6	**43328**
11	Valmi (Ilia Perfecture)	17:30 - 24/08/2007	6	**43071**
12	Klindia (Ilia Perfecture)	01:00 - 25/08/2007	7	

A set of specific procedures was used, for acquiring sufficient and objective data and ensuring observer's safety during fieldwork, as well as for the effective and efficient utilization of the obtained data in the office. In all cases, the following data were observed, measured and recorded:

a. Rate of spread of fire front or fire finger, in kilometers per hour (km/h), ($ROS_{observed}$). Observer's positions were identified by using a Garmin etrex Summit GPS device and the geographic coordinates were recorded. Photographs of the sequential locations of the fire front, were taken using a Canon Powershot S3is digital camera which has a lens with a focal length ranging from 36 mm (wide Angle) to 432 mm (telephoto). For all shots the horizontal azimuth was recorded using a compass. Thus, later in the office, fire front locations were pinpointed on the map using the ArcGIS 9.3 Geographic Information System (GIS) software by ESRI corporation. Additionally, the time of every photo capture was known from the data recorded automatically by the camera on the digital photo file that was in JPG format. By knowing the exact time for every fire front location (Alexander and Thomas, 2003a), $ROS_{observed}$ values were calculated (figure 3(a) & (b)).

1(a): Photo captured at 13:34:34 — 1(b): Photo captured at 13:35:48

Figure 3(a) & (b): Fire spread of 68 meters in tall maquis (yellow arrow), up a 96% slope (44^{o}), within a period of 1 minute and 14 seconds. $ROS_{observed}$ = 3.31 km/h.

b. Flame length, in meters (m), ($FL_{observed}$) by comparing the flames with objects of known dimensions such as trees, farmhouses, paths, etc. These data will be used in the future, for further analysis.
c. Meteorological conditions; air temperature (T) in degrees Celsius (^{o}C), relative humidity (RH) in (%) and wind speed and gusts in km/h, using an electronic weather instrument (type: Thermometer – Anemometer - Hygrometer Model N^{o} AM4205) and, moreover, wind direction azimuth, using a compass.
d. Vegetation type in which the fire spread.
e. Topographic information such as altitude, slope and aspect of the location in which the fire spread.
f. Forest fire description (surface, passive, active or independent crown fire, explosive fire behaviour, spotting, fire spreading in a narrow valley, steep canyon or on a saddle).
g. Additional general information such as presence or absence of fire fighting attempts from the air or from the ground, volunteers and civilians participation, percentage of fire containment, etc.
h. Additional description of the fire runs by keeping detailed notes about fire spread direction, topography, wind direction and wind adjustment factors (Rothermel, 1983) in order to develop a reliable, errors free and easy to handle, database. For

example, there were some observations for sideward or backward fire spread and other cases in which fire spread downslope with the wind blowing downslope, also.

Observations of fire behaviour at the time of the fire, were matched with simultaneous observations and measurements of fire weather, topography and forest fuels. As most fieldwork was performed at a small distance from the fire fronts, continuous observer movement was necessary. Thus, most field measurements and collected information were being saved in a digital voice recorder.

After the fires were extinguished, additional complimentary information was collected and assessed by interviewing local residents, forest and fire service officers and officers from local authorities, by going over the fire area with them (Byram 1954).

5. Analysis

Fieldwork was followed by processing a huge amount of various spatial and descriptive data by the GIS software in order to develop, in substantial detail, the overall picture of what happened. The most important information layers were: a) fire eruption sites, b) approximate burned areas per day (pixel size=300 m) by utilizing and combining fieldwork, maps and low resolution satellite images of the US Maryland University FIRMS system and the NASA MODIS Rapid Response System, c) total burned areas (pixel size=10 m) without recording unburned islands (by digitizing maps of the “Service Régional de Traitement d'Image et de Télédétection”, Strasbourg (Sertit) for the fires of August http://130.79.72.201/documents/greece_2007/greece_2007.html and of the World Wildlife Fund (WWF) of Greece for the fire of Parnis mountain http://www.wwf.gr/storage/additional/ParnithPosterBig.jpg that was produced by the Greek company Environet), d) observation points at the time of the fires and after the fires were over, e) horizontal azimuths of observation line for each observation point, f) locations of fire fronts at the time of each observation g) $ROS_{observed}$ values and direction of fire fronts and fingers, h) areas were spotting occurred, k) backfire or burnout zones, l) areas where different fire fronts merged, etc.

Subsequently, detailed maps and case studies of these fires were generated; these were then used for the development of the fire behaviour database. This database can be used and is available for testing any fire behaviour model.

The database constists of fire behaviour observations that took place during surface fires in maquis (evergreen sclerophyllus shrubs eg *Pistacia lentiscus, Quercus coccifera, Phillirea latifolia, Arbutus unedo,* etc.), grass, small xeric shrubs, up to 0.5 m height (phrygana) as well as during passive and active crown fires in fir (*Abies sp.*) and pine (*Pinus halepensis*) forests. For many of the crown fire records in the pine forests, there was an understory layer consisting of tall evergreen shrubs.

The analysis presented here, focuses on testing the degree of agreement of BehavePlus predictions with field observations for a specific type of fuel that is tall Mediterranean shrublands (maquis). This fuel corresponds to a fuel model for “evergreen-schlerophyllous shrublands (maquis) (1.5 - 3 m)” that has been developed for Greece by Dimitrakopoulos et al. (2001) and Dimitrakopoulos (2002). Examination of the database showed that a subset consisting of 27 records was appropriate for the analysis. In regard to type of fire, these records fall in one of the two following categories:

a. Surface fire in tall maquis shrubfields, and

b. Passive crown fire in Pinus halepensis forest with maquis understory where the fire rate of spread is determined by the surface rate of spread in the understory (Van Wagner, 1977).

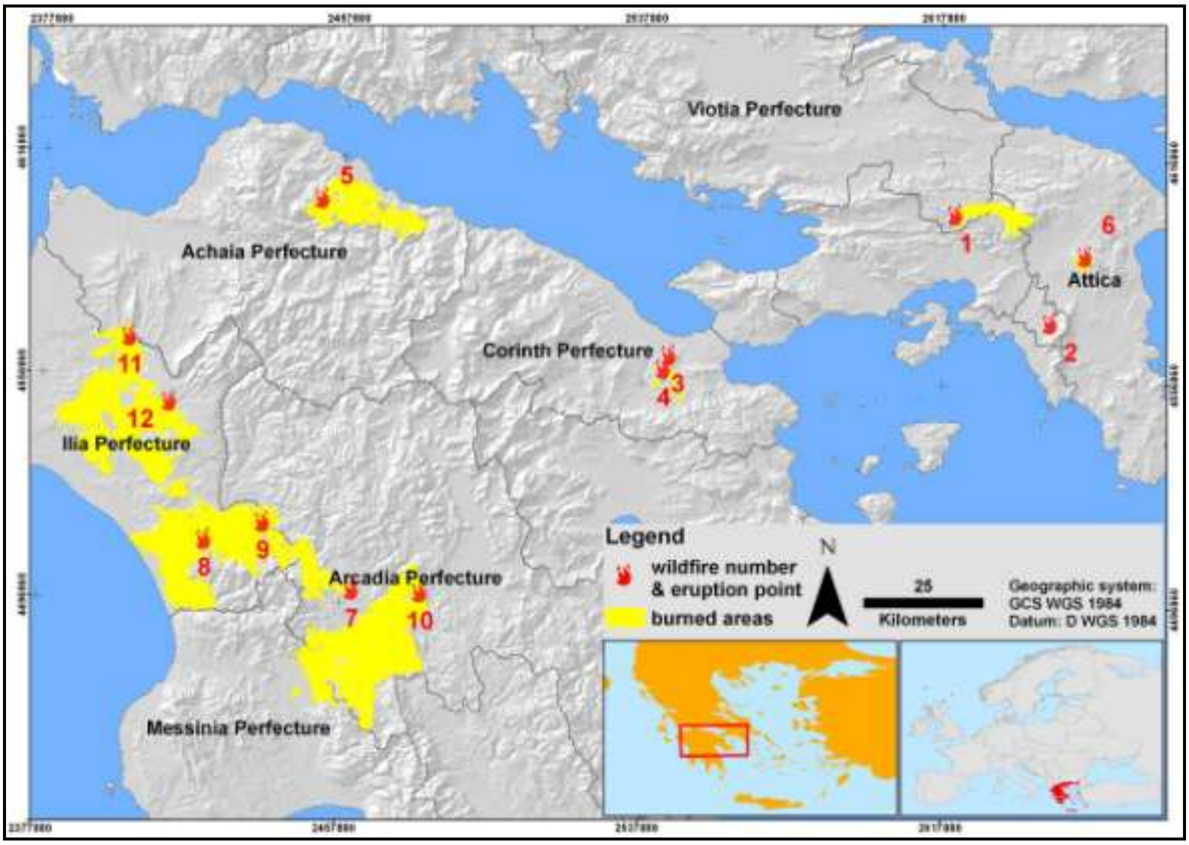

Figure 4: Burned areas of the twelve documented forest fires, numbered as in table 1, including the points where the fires started.

The sample of 27 observations, all of them refering to surface fire behaviour in tall evergreen-schlerophyllous shrubs during pure surface fires or passive crown fires, includes a maximum $ROS_{observed}$ value of 3,3 km/h, and a minimum value 0.1 km/h. The mean $ROS_{observed}$ value of the 27 data points is 1.1 km/h.

BehavePlus was used for predicting surface fire rate of spread values ($ROS_{predicted}$), using measured slope values, on-site meteorological measurements and the above mentioned fuel model for maquis. However, certain required adjustments were made to the fuel model using the NEWMDL module of the original BEHAVE system (Burgan and Rotrhermel 1984), before the model could be used with BehavePlus. These adjustements were:

a. Litter weight (3.38 t/ha), which had been reported separately in the published model, was added to the weight of fine (1-hour) dead surface fuels (14.5 t/ha), so that the total 1-hour fuel load came up to 17.88 t/ha.
b. The overall fuel bed depth was reduced to 203.58 cm from the original value of 218.00 cm as a result of adding the litter load to the rest of the 1-hour surface fuels.
c. A value of 34% was assigned to the “dead fuel moisture of extinction”. It was estimated using NEWMDL. Such a value is required for a fuel model to be complete but it had not been reported for the published model.

The values of the fuel model parameters are reported in table 2.

A second preliminary line of investigation concerns nine (9) cases of active crown fire in *Pinus halepensis* forest with maquis understory. There, following the example of Rothermel (1991), the observed crown ROS values ($ROS_{observed(crown)}$),, were compared with predictions for surface fire ($ROS_{predicted(surface)}$), that were obtained utilising the same surface fuel model for “evergreen-schlerophyllous shrublands (maquis) (1.5 - 3 m)” as above.

Table 2: The values of the parameters of the “evergreen-schlerophyllous shrublands (maquis) (1.5-3 m)” fuel model as calculated through the NEWMDL module of BEHAVE.

CURRENT VALUES OF FUEL MODEL PARAMETERS

STATIC 502. MEDITERRANEAN SHRUBS 1.5-3.0 M BY: XANTHOPOULOS

LOADS, MTON/HA		S/V RATIOS, 1/CM		OTHER	
1 HR	17.88	1 HR	55.	DEPTH, CM	203.58
10 HR	13.30	LIVE HERB	0.	HEAT CONTENT, J/G	20000.
100 HR	8.50	LIVE WOODY	55.	EXT MOISTURE, %	34.
LIVE HERB	0.00				
LIVE WOODY	10.60				

LOADS, S/V RATIOS, AND DEPTHS FOR INDIVIDUAL FUEL COMPONENTS

FUEL COMPONENT	************* LOADS *************					*** S/V RATIOS ****			DEPTHS
	1 HR	10 HR	100 H	HERB	WOODY	1 HR	HERB	WOODY	
LITTER	3.38	0.00	0.00	0.00	0.00	55.	0.	0.	3.50
GRASS	0.00	0.00	0.00	0.00	0.00	0.	0.	0.	0.00
SHRUBS	14.50	13.30	8.50	0.00	10.60	55.	0.	55.	218.00
SLASH	0.00	0.00	0.00	0.00	0.00	0.	0.	0.	0.00

************** FUEL LOAD SUMMARY **************

**** FUEL COMPONENT ****			** TIMELAG CLASS *		****** UNITS ******	
	DEAD	LIVE	CLASS	LOAD		
	-----	-----	------	-----		
LITTER	3.38	0.00	1 HR	17.88	LOAD	: MTON/HA
GRASS	0.00	0.00	10 HR	13.30	S/V	: 1/CM
SHRUBS	36.30	10.60	100 HR	8.50	DEPTH	: CM
SLASH	0.00	0.00		-----		
	-----	-----				
TOTAL	39.68	10.60	TOTAL	39.68		

6. Results

The 27 pairs of ROS observations and BehavePlus predictions, were correlated via a linear regression, using the SPSS (v.10.0) software, resulting in the following equation:

$$ROS_{observed} = 0.068 + 0.853 * ROS_{predicted} \quad (1)$$

with an adjusted R^2 = 0.744 and equation p-value <0.001. The p-value of the slope coefficient is p<0.001 as well. On the other hand the p-value of the constant of the equation is not statistically significant (p-value=0.648). In spite of this, as the value of the constant

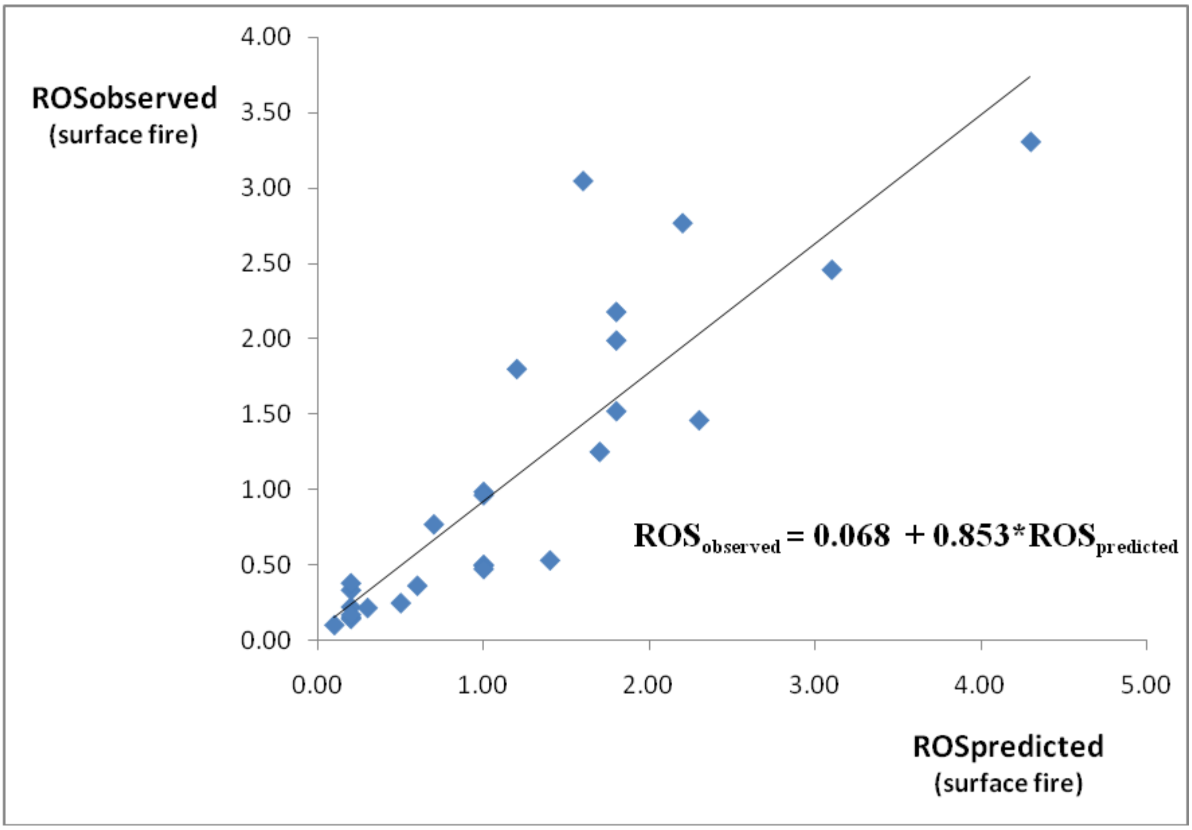

Figure 5: Correlation of surface $ROS_{observed}$ and $ROS_{predicted}$ values

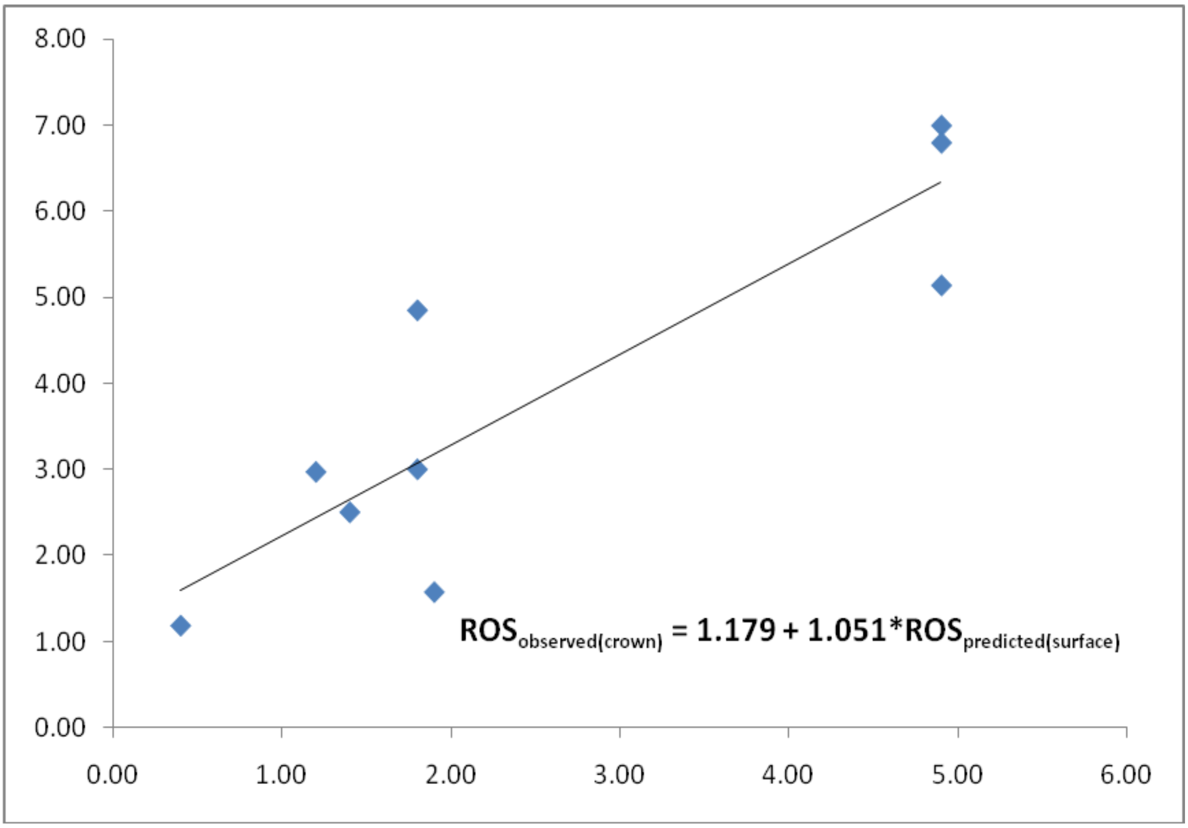

Figure 6: Plot of the regression equation between the $ROS_{observed(crown)}$ and $ROS_{predicted(surface)}$ values.

(=0.068) is quite close to zero and the value of the slope coefficient is not far from unit (1) it can be concluded that the overall agreement between observations and predictions is good. The regression equation is plotted with the data in figure 5, confirming the good agreement of predictions with observations.

The regression of the nine active crown fire ROS observations in *Pinus halepensis* forests with evergreen schlerophyllous understory against ROS predictions for surface fire in maquis fuels, resulted in the following linear regression equation (figure 6):

$$ROS_{observed(crown)} = 1.179 + 1.051\ ROS_{predicted(surface)} \quad (2)$$

with an adjusted $R^2 = 0.743$. The constant of the equation (1.179) is not statistically significant (p-value = 0,118) while the coefficient of the slope of the regression line is statistically significant (p-value = 0,002) and almost equal to the unit (1.051).

The ratio between $ROS_{observed(crown)}$ and $ROS_{predicted(surface)}$ varied between 0.83 and 2.95 with an average value of 1.81 and standard deviation 0.74. In general, $ROS_{observed(crown)}$ values tend to be slightly less than twice the values of $ROS_{predicted(surface)}$ for this fuel model. However, due to the small sample size, this conclusion can only be considered as preliminary, needing further investigation.

7. Discussion

The large wildfires that were spreading for many continuous days during the fire season of 2007 in Greece, on many occasions exhibited characteristics of extreme fire behaviour. Additionally, the large number of simultaneous conflagrations resulted in a collapse of firefighting during the critical days of that summer. Thus, many fires spread unobstructed, practically without any firefighting influence, presenting an opportunity for studying fire behaviour of a type that is not commonly observed in Greece (Xanthopoulos et al., 2009).

The dataset of 27 fire behaviour observations presented and analyzed here mostly includes data from intense fires spreading under a variety of meteorological and topographic conditions. For these 27 sets of observations that concern fire spread in tall evergreen schlerophyllous shrubs, predicted values of surface rate of spread were obtained using the BehavePlus fire behaviour prediction system. The published fuel model for "evergreen-schlerophyllous shrublands (maquis) (1.5 - 3m)" developed by Dimitrakopoulos et al. (2001) and Dimitrakopoulos (2002), was used as an input in the prediction system, after applying small required adjustments. The regression analysis that followed showed that the predicted values of surface fire rate of spread ($ROS_{predicted}$) were correlated quite well with the actual values that were measured in the field ($ROS_{observed}$).

The adjusted $R^2 = 0.744$ of the regression equation indicates that the unexplained error is relatively low. This error may be due to weaknesses in the fire behaviour model itself or errors in the inputs on which the calculations were based. As there was a strong emphasis in correct documentation of fire behaviour, weather and topography, and cases for which there were doubts were not included in the database, input errors are most likely due to weaknesses in describing the fuels. This is not surprising since a single fuel model is used to describe a variety of fuel conditions that share as common that they have been identified through visual assessement as consisting of tall (more than 1.5 m) Mediterranean evergreen-schlerophyllous shrubs. Obviously, the actual variation between the different shrub situations, resulting from differences in their height, density, and even species variation, cannot be represented by using as input just one stylized fuel model. This is common in all applications of BehavePlus with stylized fuel models as inputs, an option that partially sacrifices accuracy in favor of practicality. Similar deviations between predictions and observations have been noted in practically all testing of the fire behaviour model until now.

The analysis of active crown fires can only be considered as a preliminary effort given the limited sample size. Nevertheless, it offers a first assessment of the possibility to predict the rate of spread of active crown fires in *Pinus halepensis* forests as a function of predicted surface fire ROS in tall “evergreen-schlerophyllous shrublands (maquis) (1.5 - 3m)” that usually form the understory layer in such forests. The relatively high adjusted $R^2 = 0.743$ is not enough to inspire confidence in the regression equation which suffers from the small sample size and a constant that is not statistically significant. Apart from that, it is worth noting that the ratio of $ROS_{observed(crown)}$ to $ROS_{predicted(surface)}$ varied between 0.83 and 2.95 with an average value of 1.81. This value is in general agreement with the suggestion of Cruz et al. (2005) that rates of spread in crown fires are often twice the spread of the surface fire. On the other hand, Rothermel (1991) examined seven crown fires in conifer forests of the northern Rocky Mountains where the surface fuels could be represented by fuel model 10, “timber litter and understory” (Anderson 1982) and found that the average rate of spread for the crown fires was 3.34 times faster than predicted for surface fire, with a standard deviation of 0.59. This difference can be explained by the much lower rates of spread exhibited by fuel model 10 type fuels, when compared with shrub fuel models (Anderson 1982). Furthermore, this difference is an indication that a multiplication factor for estimating crown fire ROS from surface fire ROS such as the 1.81 factor above should be used with extreme caution. It is extremely important that the fuels beneath the canopy are described well by the fuel model used for obtaining estimates of surface fire ROS. For example, Kazanis et al. (2006) distinguished different types of understory fuel situations in *Pinus halepensis* forests in Central Greece. The shrub understory in low-elevation drier sites has very little biomass. For such forests it would be clearly erroneous to use a high biomass shrub fuel model such as the “evergreen-schlerophyllous shrublands (maquis) (1.5 - 3m)” for obtaining estimates of surface fire ROS that will then be multiplied by a factor (such as 1.81) to get an estimate of crown fire ROS.

8. Conclusions

In conclusion, based on the quite good adjusted R^2, and the level of significance of equation (1) it can be concluded that the adjusted “evergreen-schlerophyllous shrublands (maquis) (1.5 - 3m)” model can be used with acceptable confidence with the BehavePlus system for fire behaviour predictions in shrub fuel complexes of this type in Greece and probably other Mediterranean countries with similar vegetation. Further examination in a wider range of conditions is, of course, desirable in order to improve confidence and broaden possible operational uses.

In regard to predicting active crown fire spread it can only be stated that the preliminary results are encouraging, a correlation of surface fire behaviour prediction with actual crown ROS seems to exist but more work is needed before a robust equation can be developed. Such work is in progress. Data collection in crown and surface fires continues, aiming to document as many fires as possible and to develop a large database that will be available for testing any fire behaviour prediction model in the future. The authors, in agreement with numerous other fire experts (Byram, 1960, Turner et al., 1961, Thomas, 1994, Alexander and Thomas, 2003b), believe in the importance of developing an extensive file of well documented fires. Such case studies can be used as teaching aids (Chandler, 1976) and can assist in improving understanding of fire behaviour, resulting in safer and more efficient fire management (Countryman 1972).

9. Acknowledgements

The research reported here was carried out as part of the M.Sc. thesis of the first author for the post-graduate studies program on "Prevention and Management of Natural Disasters" of the Department of Geology and Geo-Environment of the National and Kapodistrian University of Athens, Greece, and also in the context of a research project of the Institute of Mediterranean Forest Ecosystems and Forest Products Technology titled "Forest fuels standardization and management methodology in Attica". The project was co-funded by the European Regional Development Fund (ERDF) through the Greek General Secretariat for Research and Technology (Project code: ATT-63).

The help of Nikolaos Zirogiannis who cooperated in post fire documentation of the burns and preparation of burned area maps in the context of his own M.Sc. thesis, is acknowledged and appreciated.

10. Bibliography

Alexander, M.E., Thomas D.A., 2003a. Wildland Fire Behavior Case Studies and Analyses: Other Examples, Methods, Reporting Standards, and Some Practical Advice. Fire Management Today, 63 (4): 4-12.

Alexander, M.E., Thomas D.A., 2003b. Wildland Fire Behavior Case Studies and Analyses: Value, approaches, and practical uses. Fire Management Today, 63(3): 4-8.

Anderson, H.E., 1982. Aids to determining fuel models for estimating fire behavior. USDA For. Serv., Research Note RM - 354. 4 pp.

Andrews, P.L., Bevins, C.D., Seli, R.C., 2005. BehavePlus fire modeling system, Version 4.0: User's Guide. General Technical Report RMRS-GTR-106WWW revised. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 132 p.

Athanasiou, M., 2008. Forest fire behavior in Greece: Characteristics and prediction. M.Sc. Thesis. Inter-University Post-Graduate Studies Programme on "Prevention and Management of Natural Disasters", Department of Geology and Geo-Environment of the National and Kapodistrian University of Athens, and Department of Geoinformatics and Topography of the Technological Educational Institute of Serres. 140 p.

Burgan, R.E., Rothermel, R.C. 1984. BEHAVE: fire behavior prediction and fuel modelling system—FUEL subsystem. Gen. Tech. Rep. INT-167. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 126 p.

Byram, G.M., 1954. Atmospheric conditions related to blowup fires. Stn. Pap. No. 35. Asheville, NC: USDA Forest Service, Southeastern Forest Experiment Station. [Reprinted as: National Fire Equipment System Publication NFES 2565 by the National Wildfire Coordinating Group, Boise, ID.]

Byram, G.M., 1960. A problem analysis and proposed research program for the Southern Forest Fire Laboratory. Macon, GA: USDA Forest Service, Southeastern Forest Experiment Station, Southern Forest Fire Laboratory.

Chandler, C.C., 1976. Meteorological needs of fire danger and fire behavior. In: Baker, D.H.; Fosberg, M.A., tech. coords. Proceedings of the Fourth National Conference on Fire and Forest Meteorology; 1976 November 16–18; St. Louis, MO. Gen. Tech. Rep. RM–32. Fort Collins, CO: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station: 38–41.

Countryman, C.M. 1972. The fire environment concept. Berkeley, CA: USDA Forest Service, Pacific Southwest Forest and Range Experiment Station.

Cruz, M. G., Alexander, M. E., Wakimoto, R. H. 2005. Development and testing of models for predicting crown fire rate of spread in conifer forest stands. Canadian Journal of Forest Research 35, 1626-1639.

Dimitrakopoulos, A.P., Mateeva, V., Xanthopoulos, G.,. 2001. Fuel models for Mediterranean vegetation types in Greece. Geotechnical Scientific Issues (Geotechnical Chamber of Greece): Series VI, vol. 10(3): 192-206 (in Greek).

Dimitrakopoulos, A.P., 2002, 'Mediterranean fuel models and potential fire behaviour in Greece', International Journal of Wildland Fire 11(2) 127 – 130.

Kazanis, D., Xanthopoulos, G., Arianoutsou, M., 2006. Long-term post-fire evolution of understorey biomass in Pinus halepensis Mill. forests of Central Greece. Abstract p. 175. In "Forest Ecology and Management", Vol. 234, Supplement 1, D. X. Viegas (Ed.), Elsevier Publishers, Amsterdam. 289 p. Full text, in Proceedings of the 5th International Conference on Forest Fire Research. November 27-30, 2006, Figueira da Foz, Portugal (on CD).

McAlpine, R.S., Xanthopoulos, G., 1989. Predicted vs observed fire spread rates in ponderosa pine fuel beds: A test of American and Canadian Systems. pp. 278-294. In proceedings of the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada. D.C. MacIver, H. Auld, and R. Whitewood, editors. 471 p.

Rothermel, R.C., 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 40 p.

Rothermel, R.C. 1983. How to predict the spread and intensity of forest and range fires. Gen. Tech. Rep. INT-143. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 161 p.

Rothermel, R.C. 1991. Predicting behaviour and size of crown fires in the Northern Rocky Mountains. Res. Pap. INT–438. Ogden, UT: USDA Forest Service, Intermountain Research Station.

Thomas, D. 1994. A case for fire behaviour case studies. Wildfire. 3(3): 45, 47.

Turner, J.A., Lillywhite, J.W., Pieslak, Z., 1961. Forecasting for forest fire services. Tech. Note No. 42. Geneva, Switzerland: World Meteorological Organization.

Turner, J.A.; Lillywhite, J.W.; Pieslak, Z. 1961. Forecasting for forest fire services. Tech. Note No. 42. Geneva, Switzerland: World Meteorological Organization.

Van Wagner, C.E., 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research. 7: 23–34.

VanWilgen, B.W., LeMaitre, D.C., Kruger, F.J., 1985. Fire behavior in South African fynbos (macchia) vegetation and predictions from Rothermel's fire model. J. Appl. Ecol. 22, 207–216.

Xanthopoulos, G., 1986. A fuel model for fire behavior prediction in spotted knapweed (Centaurea maculosa L.) grasslands in western Montana. Masters Thesis. Univ. of Montana, MT, USA. 100 p.

Xanthopoulos G., Viegas, D.X., Caballero, D., 2009. The fatal fire entrapment of Artemida (Greece) 2007. pp. 65-75. In "Recent Forest Fire Related Accidents in Europe". Domingos Xavier Viegas (Editor). European Commission, Joint Research Centre, Institute for Environment and Sustainability. EUR 24121 EN. 75 p.