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Analysis of Fire-Weather Data and Study of the Released Combustion Products from Forest Fires. Emphasis on the Health and Safety of Firefighters and Citizens on the Front Lines of Fires

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Abstract

Forest fires are a natural phenomenon that has concerned people for thousands of years and will naturally continue to exist in the years to come. The study of thermal intensity and the release of gaseous pollutants from large forest fires has gained great importance, due to the risks to human health and the increasing environmental problems of recent years. In order to limit the impacts, the application at the strategic, tactical and operational level of the estimates of forest fire simulation models and the release of air pollutants are imperative. The aim of the study is to predict the effects of the thermal intensity and the released combustion products of large forest fires. The study area is Greece, specifically the region of Attica, due to the large residential development that brings about a large number of agroforestry fires. Measurements from meteorological stations were used as tools for the study in collaboration with the Farsite forest fire behavior and pollutant release simulation model. This system allows quantitative estimations of front heat intensity and smoke concentration at the fire front for the safety and health of civilians acting as adjuncts as well as first responders working to suppress a forest fire. The simulations showed a positive correlation of wind intensity with the thermal intensity of the front as well as with the release of gaseous pollutants. Therefore, the system provides excellent decision-making support for the safety and health of personnel (first responders and civilians), from on-duty officers and forest fire fighters at strategic, tactical and operational levels.

Keywords: Forest Fires, Health and Safety, Fire-weather data, CO, $PM_{2.5}$

1. Introduction

Forest fires are among the most devastating natural disasters, characterized by their rapid spread, high intensity, and extensive environmental, economic, and social impacts. Their frequency and intensity have increased over the years due to climate change, urbanization, and poor land management practices. These fires not only destroy biodiversity and alter ecosystems but also release significant quantities of harmful pollutants into the atmosphere, posing serious health risks to humans. In particular, the safety and well-being of firefighters and residents near fire-prone areas are profoundly affected by exposure to toxic combustion products and extreme fire-weather conditions. The Mediterranean region, including Greece, is particularly vulnerable to forest fires due to its dry summers, strong winds, and diverse vegetation that serves as abundant fuel. Among the most fire-affected areas in Greece is Attica, which has experienced numerous catastrophic wildfires in recent years. These events highlight the urgent need for comprehensive studies on fire behavior and the toxicological implications of the pollutants released during combustion. Understanding the dynamics of forest fires and their associated risks is critical to developing effective strategies for prevention, response, and mitigation.

The study of fire-weather interactions is essential in understanding how meteorological conditions influence fire intensity, spread rate, and pollutant emissions. Parameters such as wind speed, temperature, and humidity play a pivotal role in shaping the behavior of a wildfire, affecting both the environment and human health. Additionally, the release of combustion products, including carbon monoxide (CO), particulate matter (PM2.5), and other toxic substances, necessitates rigorous analysis to quantify their impact on respiratory and cardiovascular health, as well as long-term implications for populations frequently exposed to such events. This study leverages advanced simulation tools, specifically the FARSITE fire behavior model, to analyze fire-weather data and predict the release and dispersion of combustion products. By focusing on the region of Attica, Greece, the research aims to provide quantitative insights into the relationship between fire intensity, pollutant emissions, and the associated health risks.

The primary objectives are to evaluate the thermal intensity of forest fires, estimate the concentration of smoke components such as CO and PM2.5, and assess their implications for the health and safety of frontline responders and affected residents. In doing so, this research contributes to the growing body of knowledge required for effective wildfire management. It offers actionable data to improve firefighting strategies, enhance public safety measures, and inform policy decisions aimed at reducing the adverse effects of wildfires. By addressing these critical challenges, the study underscores the importance of integrating scientific research with practical applications to mitigate the multifaceted impacts of forest fires in vulnerable regions.

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2. Materials and Methods

2.1 Fire Line Intensity

To measure the fire line intensity of the fire front or the heat generated by a given length of fire front in a given time, the total amount of combustible fuels in an area as well as the rate of fire spread must be taken into account. The fire line intensity can be calculated from Eq.1 [1]:

$$I = 0{,}01667 \times H \times W \times R \qquad (1)$$

where,

I = the Fire Lime intensity of the fire front in kJ/sec m or kW/m.
H = the heat generated per mass of fuel in kJ/kg (the heat rate).
W = the mass of fuel available per unit area in kg/m^2.
R = the rate of fire spread in m/sec.

The fire line intensity, also referred to as Byram intensity [2], is the most common and most useful measure of fire intensity and is measured in kW/m. It depends on the heat released per unit area and the rate of fire spread and is equivalent to the heat released from a unit of front length in a unit of time [3]. There is a correlation of flame length and fire line intensity values with fire suppression actions (Table 1). Also, a variation of surface rate of spread according to the heat released per unit area [4].

Table 1. Correlation of flame length and Fire Line intensity values with fire suppression actions

Flame length (m)	**Fire Line Intensity (kW/m)**	**Suppression Methods**	
< 1,2	< 350		The fire can generally be managed by direct frontal or lateral attack, using personnel with hand tools and manual fire line excavation.
1,2 – 2,4	350 – 1.750		The fire is intense enough for direct frontal attack by forest firefighters with hand tools. The manual fire line cannot hold the fire. Mechanical means such as excavators, fire hydrants, fire trucks and aircraft with retardant fluids may be effective.
2,4 – 3,4	1.750 – 3.500		Fires can have serious control problems, because of crown fires, spotting and reignitions. Control efforts at the front of the fire become rather ineffective.
> 3,4	> 3.500		These are large wildfires of high intensity that are difficult to bring under control. Crown fires with spotting and high spread rates are possible. Direct methods are considered dangerous and ineffective. Indirect methods of suppression should be applied, using aerial means (aircraft, helicopters) and creating a firebreak at a safe distance from the front of the incoming fire.

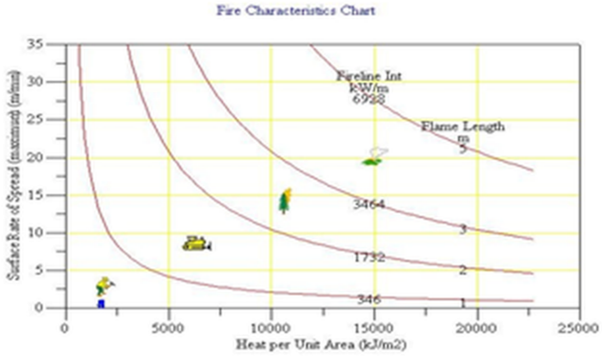

Fig. 1. Variation of surface rate of spread according to the heat released per unit area - categories according to the suppression actions in Table 1 [4].

2.2 Forest fire Smoke

Smoke from forest fires is a complex mixture of carbon, liquids and various gases (including carbon monoxide, aldehydes, nitrous oxides, peroxides, and acids). The solids and liquids are likely to contain carcinogens, irritants, and trace metals. Smoke toxicants can be analyzed in liquid particles or absorbed during the solid-to-gas or liquid-to-gas conversion phases [5,6,7]. Most of the toxicants found in the smoke aerosol are probably carcinogens and toxic trace metals. This toxicity is related to long-term exposure to such conditions. For shorter periods of time, the toxic effects are mainly due to gases such as carbon monoxide and sulphur dioxide where the aerosols act mainly as irritants. Carcinogens are substances that cause cancer if they come into contact with the skin or if inhaled through the lungs. Trace metals and their compounds such as mercury, lead and cadmium can be highly toxic in aerosol form.

At a certain size their particles can penetrate and become lodged in the pulmonary alveolus. Their absorption from the blood through the pulmonary alveolus is a much more potent process (in the order of 80%) than absorption through the intestinal wall (about 15%). Toxicity depends on the nature of the compound [8,9].

The physical characteristics of smoke are important because of their effect on the way smoke spreads, human health and visibility. Particle size and shape, absorption properties, density and refractive index all contribute to reducing visibility from smoke. Many of these characteristics are also important in describing the effects on human health. Inhalation and retention by the lungs depends directly on the size of the particles. Particles smaller than 2.0 millionths of a meter penetrate deeper into the lungs and are more dangerous [10].

Recent reviews on the cardiovascular [11] and respiratory [12] impacts of wildfire smoke found that while most primary studies on cause-specific mortality reported positive associations, only a few had statistically significant risk estimates, and some studies showed no association at all. However, a meta-analysis by Karanasiou et al. (2021) found a significant increase in the risk of cardiovascular mortality on smoky days compared to non-smoky days [13].

There is growing evidence suggesting possible links between exposure to wildfire smoke and wildfires and an increased risk of neurological issues (e.g., cognitive impairment), cancer, and conditions affecting the skin and eyes [14,15]. However, there is limited data on the long-term effects of wildfire smoke exposure, which is partly due to the sporadic nature of wildfires, seasonal and geographic variations in smoke exposure, and the challenge of distinguishing wildfire-related PM2.5 from PM2.5 from other sources [16,14].

In order to address operationally a forest fire and in particular the extinguishing smoke it is very important to respond immediately with strong ground and air forces. Ground forces must carry personal protective equipment (masks with filters and protective glasses). The incident commander should be kept informed of changes in atmospheric conditions, especially wind changes, and in the case of a settlement being at risk from fire or fire smoke, he can recommend the safe evacuation of the inhabitants.

2.3 Case Study

The study area is Greece and specifically the area of eastern Attica, due to the high residential development brought about by numerous agroforestry fires, where their smoke will affect quite a lot of volunteers and people living in the area. Eastern Attica is characterized by the typical dry Mediterranean climate. Most of the year it does not rain except in the autumn and winter months. Average wind speeds are high in winter-summer with mostly NW-NE winds. The topography and the breeze in many cases can differentiate the direction of the winds. The results could be generalized more broadly to other regions with similar conditions, having dry Mediterranean climate.

As tools for the study, measurements from meteorological stations were used in cooperation with the Farsite forest fire behaviour and pollutant release simulation model. Measurements from the weather stations in eastern Attica (El. Venizelos and Marathon) showed that the maximum temperature on a dangerous day in July in terms of the occurrence and rapid spread of a forest fire can reach 39 ºC in Rafina and Nea Makri at 15:00. Wind speed is usually greater than or equal to 30 Km/h (5 Beaufort). The direction is usually northeast (NE), while the value of the wind speed is usually higher or equal than 30 km/h. Humidity may be close to 20%. Dead fuel moistures range 1hr 6%, 10hr 6% and 100hr 10%. Moisture content of live grass fuel: 100% and woody fuel: 100%.

For this site, canopy height was estimated in the literature at 10 m (the average of 4 m to 16 m), crown base height was estimated at 4.8 m (the average of 3 m to 6.5 m), crown bulk density was estimated at 0.16 kg/m^3 (average of 0.09 kg/m^3 to 0.22 kg/m^3), and duff loading density was estimated at 14 Mg/ha (average of 9.6 Mg/ha to 18 Mg/ha) [17].

The Farsite model (Table 2) in the specific study area has been calibrated with the appropriate fuel models to produce reliable results in previous work [18]. This is especially needed for Mediterranean ecosystems, where plant communities are characterized by high heterogeneity and complexity.

Due to the large spatial and temporal heterogeneity that characterises forest fuel, it is very difficult to measure its physical and chemical properties, so the creation of representative fuel models is the most used method for its valuation worldwide [19]. Fuel models are the creation of an attempt to classify vegetation species based on their physicochemical properties during combustion and are used to classify fire-prone vegetation. They are useful because they standardise a variety of complex and difficult to measure fire parameters.

Various methods of fuel modelling are being explored around the world for forest fire management. In Greece, representative fuel models for the most important forest types have been developed by Dimitrakopoulos et al. [19] and by Dimitrakopoulos [20] which can be used operationally if evaluated in relation to real fires. The thirteen (13) fuel models originally developed for the Behave Fire Behaviour Prediction System by Andrews [21], where vegetation classification was based on in situ measurement of fuel (Table 3). Therefore, for the study area (Rafina-Neos Voutzas, South Attica), each land cover type was initially matched to one of the thirteen (13) combustible matter models according to Anderson [22]. The area is covered by typical Mediterranean vegetation with dominant species being: Pinus halepensis, Kermes (Quercus coccifera), Phillyrea latifolia, Pistacia lentiscus and Genista acanthoclada. Fire and combustion products were simulated for three hours (from 15:00 to 18:00) using the Farsite fire spread model. For the study area, (Rafina - N. Voutzas) - eastern Attica) each land cover type was matched with one of the thirteen (13) fuel models according to Anderson [22], so by photo interpretation fuel models 2,3,7,8 and 10 were used [23].

Table 2. Input data in the FARSITE fire model

Input data in the FARSITE fire model	
Crown Height	10 m
Height of the beginning of the living crown	4,8 m
Bulk Density	0,16 kg/m^3
Density of fallen leaf litter	14 Mg/ha
1-hr dead fuel moisture	6%
10-hr dead fuel moisture	6%
100-hr dead fuel moisture	10%
Moisture content of live grassland fuel	100%
Moisture content of live woody biomass	100%
Simulation time step	30 min
Visual simulation step	30 min
Perimeter analysis	60 m
Spreading distance analysis	30 m

Table 3. The fuel models developed for the BEHAVE fire behaviour prediction system by Andrews

Fuel Fire Model	**Description**
1	Short grasses
2	Timber (grass and understory)
3	Tall grass
4	Chaparral
5	Brush
6	Dormant brush, hardwood slash
7	Southern rough
8	Closed timber litter
9	Hardwood litter
10	Timber (litter and understory)
11	Light logging slash
12	Medium logging slash
13	Heavy logging slash

2.4 Farsite fire model

Farsite (Fire Area Simulator), is a spatio-temporal model simulating the spread and behaviour of fires as a function of landscape, fuels and weather. Farsite is one of the main fire simulation systems developed in the last decade to describe the spread and behavior of forest fires in the field. It mainly calculates fire intensity, spread rate, burned area and release rate of some of smoke components (such as CO, CO_2 and $PM_{2.5}$) for numerous points along the landscape using Rothermel's fire behaviour model [24].

With regard to crown fires, Farsite combines Rothermel's [24,1] model with Van Wangner's [25,26] crown fire criteria to simulate surface to crown fire transition and uses Albini's model [27] to simulate the distance that fuels are thrown [28]. The procedure is actually very close to the widely used methods adopted manually for the same purpose [29]. The difference is that the process is automated, faster, and more detailed.

Farsite required data for fire simulation are the factors that form the fire triangle (topography, fuel characteristics and weather conditions). The spatial raster data used are elevation, slope, aspect, fuels, canopy cover, canopy height, crown base height, and crown bulk density (Figure 2). The first five spatial data are necessary to simulate a surface fire. The remaining three spatial data, namely, canopy height, crown base height, and crown bulk density, are also required for simulating crown fires. All these spatial data are imported and finally contained in a landscape file (with the extension LCP). The landscape file contains both the data related to the terrain and its morphology and the fuel data.

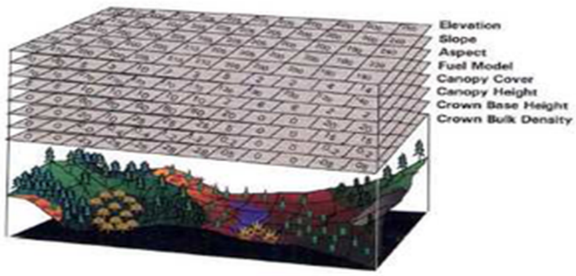

Fig. 2. Spatial data required for simulation in Farsite

Knowledge of crown cover is essential for calculating shading and wind speed reduction. Crown cover is the horizontal percentage of land covered by tree crowns. Coverage units are entered into Farsite with numbers (categories) 1-4 corresponding to the following percentage units (%). The number 0 or 99 indicates zero crown cover. The categories should be graded as follows:

1: 1-20%
2: 21-50%
3: 50-80%
4: 81-100%
0 ή 99: 0%

Crown height combined with crown cover is used to calculate wind reduction to a height of about 6 m above the ground surface [30], the flying distance of fuels and the characteristics of the overlying fire [27]. Live crown initiation height, combined with fire line intensity and foliar moisture, is important in determining the transition of a surface forest fire to crown fire [25,31]. Also, crown bulk density is a critical parameter in determining the propagation characteristics of crown fires [25,26].

The meteorological data are divided into two files (.txt). One file contains temperature, humidity, and precipitation data used to calculate changes in dead fuel. The other file contains wind speed - wind direction and cloud cover data used in the general prediction of fire behavior.

Farsite model results would be expected to suffer where strong interactions of wind and terrain are present. Furthermore, calculations that depend on fuel temperature and moisture may not be accurate where shadows are cast by topography, precipitation varies elevationally or spatially, or water availability is significantly is altered (e.g. higher fuel moistures near streams). Moreover, some problems may be a result of inaccurate data on fuel moistures, fuel descriptions (e.g. models), and weather.

Also, wind reduction factors for forested areas and lee-side topographic sheltering can undoubtedly cause errors for spread rate calculations on some parts of a landscape. The nonlinear relationship between wind speed, fire acceleration, and fire spread rate means that the average wind speed cannot be expected to predict the average fire spread rate [32] and the amount of pollutants, such as carbon monoxide and fine particulate matter (PM2.5), released into the atmosphere. Logically, a fire growth simulation should be most accurate when using accurate data at high spatial and temporal resolution.

3. Results and Discussion

A possible fire in eastern Attica was simulated with a start at 15:00 and extinguishment at 18:00 in July. The analysis time step of 30 min, perimeter visualization step every half hour, perimeter resolution of 60 m, spread distance resolution of 30 m were used and the possibility of crown and spotting fire generation and growth was selected as illustrated in Fig 3 – 6.

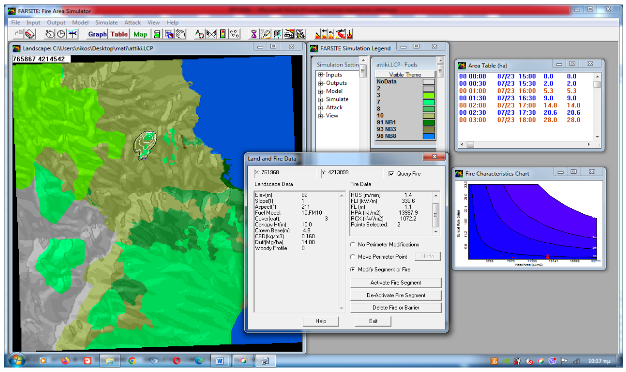

Fig. 3. The simulation of the forest fire in eastern Attica with wind intensity at 30 Km/h and thermal intensity in some parts of the perimeter at 330.6 kW/m

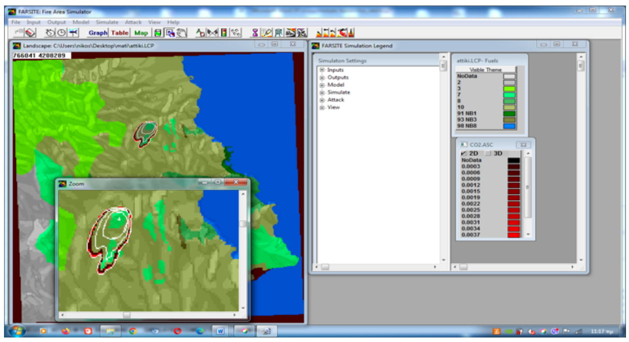

Fig. 4. The simulation of the forest fire in eastern Attica with a wind intensity of 30 Km/h and a CO_2 release rate along the fire front of 0.0037 Mg/ha/min

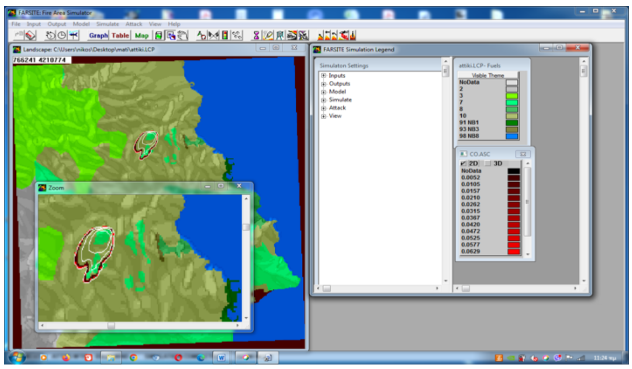

Fig. 5. The simulation of the forest fire in eastern Attica with wind intensity at 30 Km/h and CO release rate along the fire front at 0.0629 Mg/ha/min

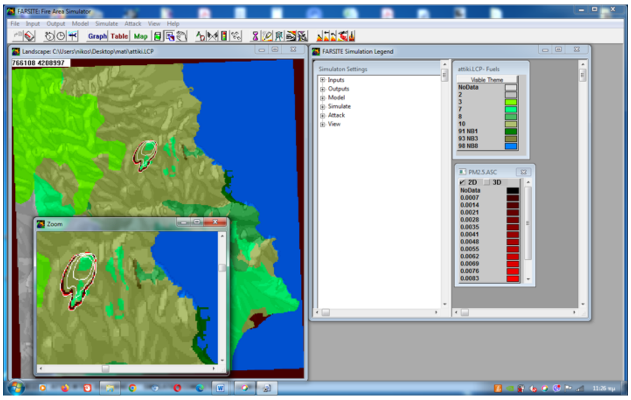

Fig. 6. The simulation of the forest fire in eastern Attica with a wind intensity of 30 Km/h and a $PM_{2.5}$ release rate along the fire front of 0.0083 Mg/ha/min

Farsite simulated the fire for a wind speed of 40 Km/h. Fire Line intensity at some points on the perimeter was at 482.4 kW/m, flame length was at 2.1 m and burned area was 41.3 ha (Figure 7). The CO_2 release rate along the fire front was close to 0.0050 Mg/ha/min (Figure 8). The CO release rate along the fire front is approaching 0.0876 Mg/ha/min (Figure 9). Similarly, the $PM_{2.5}$ release rate along the fire front is approaching 0.0110 Mg/ha/min (Figure 10).

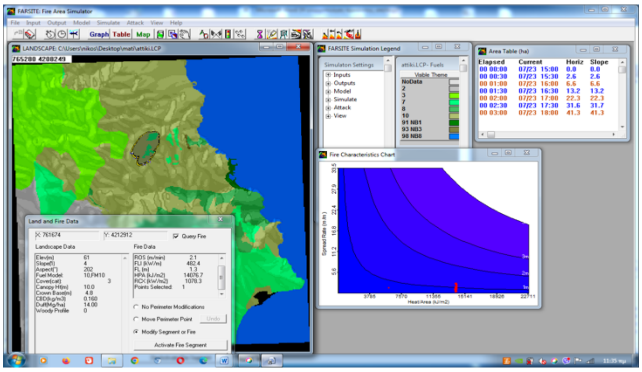

Fig. 7. The simulation of the forest fire in eastern Attica with wind intensity at 40 Km/h and Fire Line intensity in some points of the perimeter at 482.4 kW/m

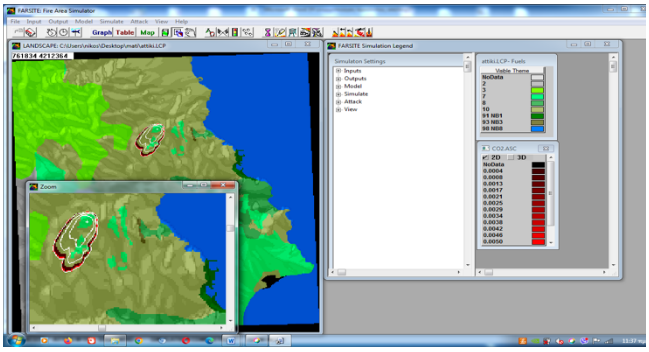

Fig. 8. The simulation of the forest fire in eastern Attica with a wind intensity of 40 Km/h and a CO_2 release rate along the fire front of 0.0050 Mg/ha/min

Finally, Farsite simulated the fire for a wind speed of 50 Km/h. Fire line intensity at some points on the perimeter was at 849.1 kW/m, flame length was at 3.6 m and burned area was 51.6 ha (Figure 11). The CO_2 release rate along the fire front was close to 0.0083 Mg/ha/min (Figure 12). The CO release rate along the fire front is approaching 0.1497 Mg/ha/min (Figure 13). Similarly, the $PM_{2.5}$ release rate along the fire front approaches 0.0174 Mg/ha/min (Figure 14).

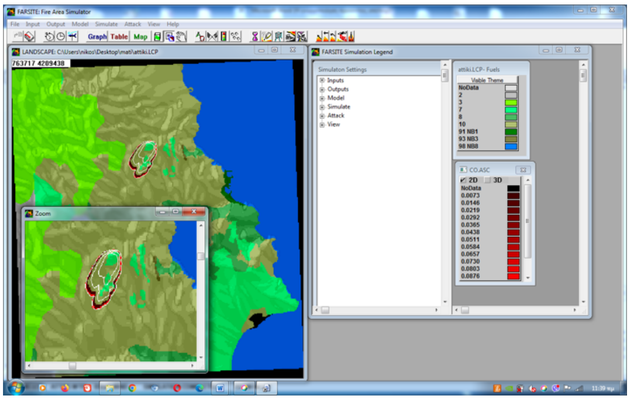

Fig. 9. The simulation of the forest fire in eastern Attica with wind intensity at 40 Km/h and CO release rate along the fire front at 0.0876 Mg/ha/min

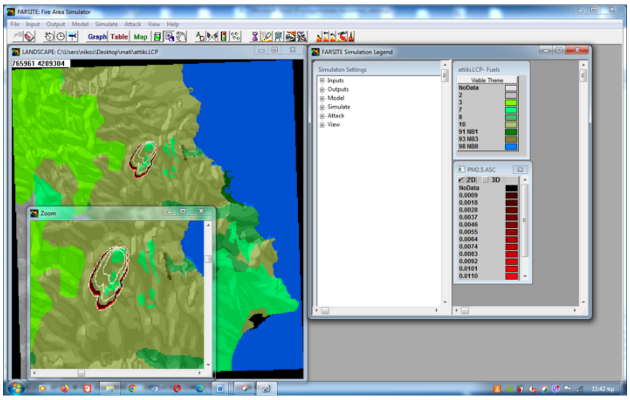

Fig. 10. The simulation of the forest fire in eastern Attica with a wind intensity of 40 Km/h and a $PM_{2.5}$ release rate along the fire front of 0.0110 Mg/ha/min

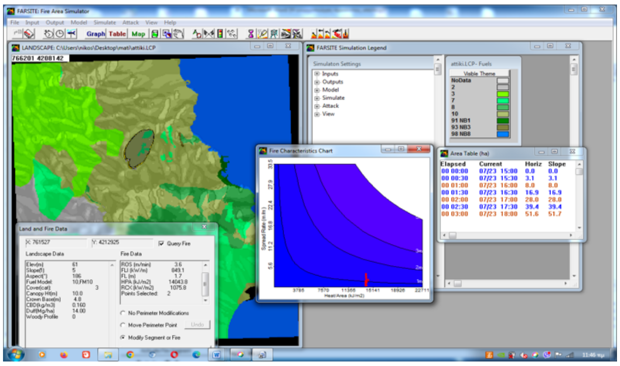

Fig. 11. The simulation of the forest fire in eastern Attica with wind intensity at 50 Km/h and Fire Line intensity in some parts of the perimeter at 849.1 kW/m

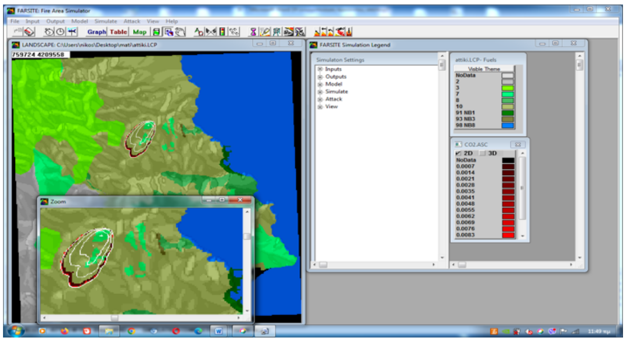

Fig. 12. The simulation of the forest fire in eastern Attica with a wind intensity of 50 Km/h and a CO_2 release rate along the fire front of 0.0083 Mg/ha/min

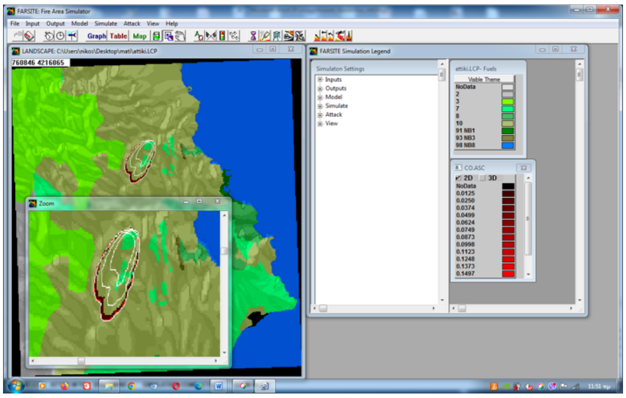

Fig. 13. The simulation of the forest fire in eastern Attica with wind intensity at 50 Km/h and CO release rate along the fire front at 0.1497 Mg/ha/min

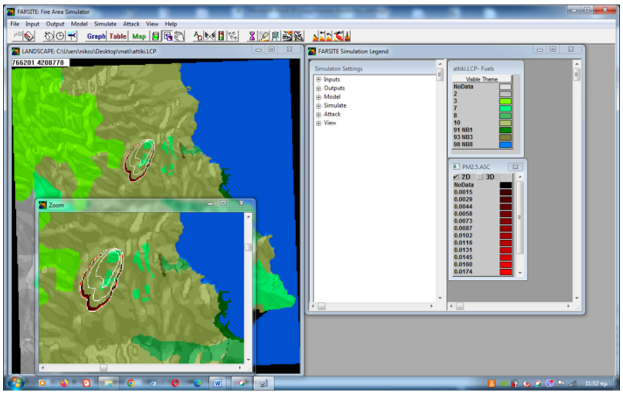

Fig. 14. The simulation of the forest fire in eastern Attica with a wind intensity of 50 Km/h and a $PM_{2.5}$ release rate along the fire front of 0.0174 Mg/ha/min

4. Conclusions

The simulations have shown a positive correlation between wind intensity and Fire Line intensity of the front, flame length and rate of spread of the fire as well as with the release of produced gaseous pollutants. Therefore, the system provides important information related to the safety and health of personnel (first responders and citizens) from officers on duty and those who are responsible for forest fire suppression at strategic, tactical and operational levels.

In addition, this system allows for quantitative estimates of the Fire Line intensity and the concentration of some smoke components such as CO, CO_2 and $PM_{2.5}$ in the front of the fire in order to ensure the safety and health of the civilians acting in an auxiliary role as well as the first responders operating to suppress a forest fire.

The study focuses heavily on the region of Eastern Attica, Greece. While this is a significant area for wildfires, the findings could be generalized more broadly to other regions which having dry Mediterranean climate.

This provides an opportunity to put the public on alert prior to any prescribed fire operation without the possibility of ending up in significant smoke danger. The system provides excellent assistance in decision making by officers on duty and those responsible to give approval for prescribed fires. It can also be used to predict the spread of smoke from industrial and uncontrolled fires.

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