Article

Fuel Treatments and Potential Fire Behavior in Peri-Urban Forests, N. Greece

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Abstract: The peri-urban and urban forests in Greece occupy a total area of 105.353 ha. In these vulnerable ecosystems, fire constitutes a natural disaster presenting particular challenges and specific difficulties. These include the high number of visitors as well as forests characteristics - such as the presence of particularly flammable tree species and high accumulation of combustible biomass – that make the on-start of fires more likely. The main purpose of the current research is to identify the optimum combination of silvicultural treatments to efficiently reduce potential forest fire severity and to facilitate their successful suppression by firefighting crews. In order to simulate the basic fire environment of urban forests, two main experimental plots were established and several tree and topographical characteristics were measured. Additionally, the NEXUS wildfire system was used to simulate forest fire potential behavior before and after the adoption of the silvicultural treatments that altered critical characteristics of the forest fire environment. The results clearly show that specific silvicultural prescriptions altered the type of forest fire spreading potential, revealing the overall efficiency of preventing actions during forest management.

Keywords: urban forests; silvicultural treatments; NEXUS; simulation; fire

1. Introduction

Fire is the most frequent natural threat to forests and wooded areas of the Mediterranean basin. Despite the fact that they constitute an integral part of the ecosystems in the Mediterranean basin [1], they destroy more forests than all other natural combined threats, such as parasite attacks, insects, tornadoes, snow and frost. Unlike other parts of the world where a large percentage of fires are naturally caused (especially by lightning), the Mediterranean basin is marked by the prevalence of human-induced fires. Natural causes are responsible for only a small percentage of all fires (1-5%) [2].

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During the last 30 years, destructive forest fires burned millions of hectares of forest in Greece. The most devastating incidents took place in Lesvos 1982, Samos 1983 and Ikaria 1993 [3,4,5], Attika 1984 [6], Thasos 1985 and 1989 [7,8,9], Thessaloniki 1997 [9,10], Chalkidiki 1990 and 2006, Peloponnese and Evia 2008 [12]. The peri-urban forests are very vulnerable to fire occurrence and spread. Covering 105,353 hectares in Greece, peri-urban forests were mainly a result of afforestation activities by the Forest Service during the 1950s [13]. However, the rapid urban sprawl into bordering forested and agricultural land creating a wildland-urban interface (WUI) – a new regime of land use intermix typical in a typical Mediterranean landscape. Nevertheless, the main issue is the steadily growing interface between wildland and urban areas, in particular with the development of diffuse individual house construction, as a result of loose policies in the approval of building permit. A relationship between the spatial repartition of forest fire ignition points and wildland urban interface has been suggested [14].

Studies have shown that around three quarters of peri-urban forest fires start in the WUI, and most of them in areas with combining both high vegetation and house densities. Moreover, when forest fires break out the priority in fire suppression is – naturally – given to the protection of people and properties, leaving the forest to burn [15, 16]. As a consequence, many ecosystems and human populations have become increasingly vulnerable to large and severe fires [17].

Peri-urban forests fires constitute a natural disaster, with many particularities and specific difficulties. Fires of peri-urban forests is a problem that in the last twenty years has become a distinctive and of high importance theme drawing great interest from scientists and professionals dealing with forest fires worldwide [18, 19, 20, 21]. In addition, fires in the suburban zone are very frequent in Greece. During 2000-2011, 2,692 fires were recorded only in the Attiki region [22]. The suppression of the suburban fires present some difficulties related to the following characteristics of the fire environment [23], such as:

- high risk of human life loss
- existence of properties e.g. homes, businesses
- possible existence of significant differences in the composition and distribution of the fuel space
- potential impact on the environment components (fuel, wind) buildings and other residential development elements in the area
- existence of infrastructure such as roads, water points, electricity and telephone networks etc.

Key element in firefighting activity is to prevent aspects of fire behavior which confound successful suppression, by altering fuel characteristics of the fire environment. A significant number of studies have been contacted on methods of fuel treatment for lowering a wildfire's severity [24, 25, 26, 27, 28, 29]. In the majority of these studies, the evaluation of fuel treatment effectiveness has been mainly based on the application of several fire models such as FARSITE, FlamMap and NEXUS, simulating wildfire behavior before and after the establishment of various silvicultural treatments. However, few studies have evaluated the effectiveness of fuel treatments at the stand level in Mediterranean species [30].

The aim of this study was to assess the potential effectiveness of simulated silvicultural treatments on wildfire severity in peri-urban pine forests in Greece. The research is based on two installed sample plots across two typical peri-urban forests located in Northern Greece. Since real experiment is impractical and unacceptably

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risky, simulation is an alternative approach to testing potential fuel treatment effectiveness [31].

2. Material and methods

2.1. Study area

The study areas were located in the urban forests of Thermaikos municipality, 20 km northwest of Thessaloniki, Greece (40°31΄N, 23°37΄N) along the road "Thessaloniki - Ag. Triada - N. Michaniona" crossing the districts Peraia - N. Epivaton and Agias Triadas. The climate is typical Mediterranean, with clear continental influence during the different seasons: the temperature presents higher values in July (26.6°C) and the lowest in January (5.2°C), the annual temperature range exceeds 20°C, while during the cold season sudden very cold air masses occur and often freeze water surfaces. Characteristic also are the mild and sunny days that happen around the middle of winter. The annual average relative air humidity rises to 78.11% and the average annual rainfall at 431.5 mm. Wind direction differs seasonally: a northern dominates during the winter coming from the Axios river Valley (Vardar), in the spring the most frequent are southwest (sea breezes), and the summer is dominated by northern and southwestern winds (sea breezes).

The Thermaikos municipality area is characterized by crystal and sedimentary rocks. Within the areas of interest, the dominant tree vegetation consists of artificial pine stands (*Pinus halepensis* & *brutia*) and cypress (*Cupressus sempervirens*) along the road Perea -N. Epivates -St. Triada and Quercus ilex. Also in the region can be found:

- ➢ herbaceous vegetation mainly in riverbeds in the urban area, with characteristic species *Phragmites communis*, *Typha angustifolia* and *Xanthium strumarium.*
- ➢ shrubby vegetation of the river bed and slope streams, with characteristic species of *Rosa* sp., *Rubus canescens*, *Ramnus rupestris* and *Asparagus* sp.
- ➢ other tree vegetation, located mostly on steep slopes from the side of the road to the hinterland. Other species that appear are *Ulmus campestris*, *Salix* sp., *Populus alba* and *Tamarix* sp.

2.2. Experimental design and sampling

The effects of silvicultural treatments for reducing fire’s potential severity in urban forests were evaluated in two plots (20m x 25m), by estimating several dendrometric characteristics of each tree located within these plots (Figure 1). The two plots were selected for their different structure which was typical for the peri-urban forest. At the first plot was not treated, while at the second plot all shrubs were cut (mechanical clearcutting) and pines pruned to the height of 2m from the ground by the managing local authorities.

In both plots a series of observations were recorded at tree and stand level, such as the total numbers of stems, the height (H) of each tree, the canopy base height (CBH) and diameter at breast height ($DBH_{1.30}$). The CBH corresponds to the average distance between the lowest continuous live or dead branches of the tree canopy down to the ground [32]. In addition, inside small rectangular plots (1 m x 1 m), we evaluated the ground biomass and moisture by collecting plant litter and plants. For the needs of the research, five rectangular subplots per experimental plot were established. Samples were transported to the laboratory in airtight containers, weighted, oven dried for 24 h

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at 105°C and then reweighed [12]. The slope of each plot was estimated using a Meridian clinometer as well as the canopy cover through a spherical densiometer [33].

Figure 1. Photos of typical forest structure of the two experimental plots. (Left: untreated / Right: Treated)

Figure 2. Collecting plant debris and plants in the rectangular plot.

2.3. Fuel characteristics

2.3.1.Aerial fuel

The allometric equations for *Pinus halepensis* Mill. proposed by Mitsopoulos and Dimitrakopoulos [34] were used for the estimation of the total Canopy Fuel Load (CFL). Based on the above equations, the available crown fuel load (needles and branches 0.0-0.63cm) for each tree was calculated. The CFL was estimated by summing the available fuel load of each tree and diving it to the area occupied by each experimental plot (500 m^2). The total above ground biomass fuel was considered to be uniformly distributed and continuous. Also the Canopy Bulk Density (CBD) was estimated by diving CFL to the average canopy length of the individuals of each sample plot [35, 36].

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2.3.2.Surface fuel

The data obtained from the installed subsample plots led to the creation of custom fuel models for the area, following the methodology proposed by Scott and Burgan [37] and the NEWMDL tool of the BEHAVE modeling system [26]. Surface fuels divided into four classes, based on the diameter of each component (1 h, 10 h, 100 h, and 1000 h). The surface per volume ratio (SAV – m^2/m^3), the heat content (kj/kg) and the extinction moisture obtained from Dimitrakopoulos and Papaioannou [38], Fire Star [39] and Bacciu [40].

2.3.3.Simulation

The NEXUS modelling system has been widely used by many researchers to evaluate the effectiveness of fuel treatment scenarios. It provides the possibility to calculate key indicators, such as Torching Index (TI) and Crowning Index (CI) that allow direct comparison of the effectiveness of various possible scenarios arising from silvicultural treatments [41]. The NEXUS modelling system from the array of available models, couples the most widely used for this analysis: Rothermel's surface [42] and crown fire models [43] and Van Wagner's models [44] of transition to crown fire [45, 46, 47, 46].

2.3.4. Silvicultural Treatments

At first stage, the current conditions of fuel regime was used as input to the NEXUS simulation system so as to estimate the potential fire behavior by calculating critical values of fire front (Rate of Spread, Fireline Intesity, Flame Length and CI). In the second stage, the effects of thinning and clearings were evaluated by reducing the corresponding stand parameters while keeping the same weather and topographical conditions. The treatment of mechanical removal of the understory (clearings) was simulated in the first plot by replacing surface fuel load with pine litter and debris, obtained by plot 2. Furthermore, the thinning effects applied only in plot 2 by reducing the basal area and the corresponding canopy fuel load to 25% from the initial value. It was theorized that tree cutting would not change the surface fuel load significantly, following the findings of Silva [48] in a Mediterranean-type ecosystem.

3. Results

Table 1 presents the main physical and chemical properties of the mean values of total surface fuels in each plot. The mean value of litter's surface biomass measured in the first experimental plot surface was 1,640 kg/m^2 and for the second experimental plot 2,020 kg/m^2. The highest values of litters' surface load on the second plot may be attributed to the clearings effects and the remained biomass during mechanical treatments.

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Table 1. Physical and chemical properties of the total sample

Properties	Custom Fuel Model	
	CFM 1: Shrub (kermes oak)	**CFM 2: Pine litter**
1h (tonne/ha)	1.232	1.109
10h (tonne/ha)	0.408	0.522
100h (tonne/ha)	-	0.389
Live Herbaceous Fuel Load (tonne/ha)	-	-
Live Woody Fuel Load (tonne/ha)	8.857	-
1h SA/V (m^2/m^3)	2,427	6,249
Live Herbaceous SA/V (m^2/m^3)	-	-
Live Woody SA/V (m^2/m^3)	5,960	-
Fuel Bed Depth (m)	1.977	0.210
Extinction Moisture (%)	25	35
Dead Heat Content (kJ/kg)	19,460	22,137
Live Heat Content (kJ/kg)	19,460	-

Table 2indicates the main dendrometric data measured in the field. The values consist of the imputed data to NEXUS simulation system in order to estimate the potential fire behavior. Fuel moisture content values (percent) by size class for seasonal moisture conditions was estimated using NEXUS module for estimating moisture content (Table 3) and the “Normal Summer” moisture values proposed by Rothermel [42]. The shading parameter follows the values obtained from Canopy Cover estimation (%).

The simulation results before treatments for the first and second experimental plots are presented in Table 4.

Table 2. The primary data of the two experimental plots

	Experimental plot 1	**Experimental plot 2**
Stems per hectare	460	360
Diameter at Breast Height (cm)	20.16	30.27
Tree Height (m)	12.27	17.19
Basal Area (m^2/ha)	16.16	27.40
Crown radii	4.19	6.5
Canopy Base Height (m)	4.97	10.57
Canopy Fuel Load (kg/m^2)	0.577	0.862
Crown Bulk Density (kg/m^3)	0.079	0.134

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Table 3. Weather scenarios and topographical conditions used for the simulation

Weather	**Inputs**
Temperature (°C)	31.5 – 42.4
Relative humidity (%)	20-25
Month	August
Hemisphere	Northern
Time	15:00-17:00
Wind (km/h)	25
Wind direction	Upslope
Shading (Canopy Cover - %)	>51
Topography	
Slope (%)	30
Aspect	East

Table 4. Fire behavior according to NEXUS outputs before treatments

Pyric parameters (before treatment)	Plot	
	1	2
Fire type	Passive crown fire	Intermediate crown fire
Rate of spread (m/min)	18.63	15.3
Fireline Intesity (kW/m)	19,153	7,737
Flame length (m)	18	10.4
Crowning Index (km/h)	35.6	26.4

Our hypothesis was that that removing 25% of the initial basal area has not reduced canopy cover lower than 50% and the moisture content of the surface fuels remained stable. However, during heavy thinning (50%) the canopy cover reduced significantly and the moisture content re-calculated, using canopy cover input lower than 50%. The simulation results after silvicultural treatments are presented in Table 5.

Table 5. Fire behavior according to NEXUS outputs after treatments

Pyric parameters (after treatment)	Plot		
	1	2 (25%)	2 (50%)
Fire type	Surface fire	Surface fire	Surface fire
Rate of spread (m/min)	1.46	0.81	0.87
Fireline Intesity (kW/m)	149	82	93
Flame length (m)	0.8	0.6	0.6
Crowning Index (km/h)	35.6	33.3	44.3

4. Discussion

The basic objective of silvicultural treatments is to prevent the initiation and the propagation of a crown fire in order to create favorable conditions for fire-fighting crews to launch a successful attack. In this sense, Loureiro and Fernandes [49] set the level of 2,000kW/m as the maximum withstandable fireline intensity for the firefighting ground forces, while beyond 4,000kW/m indirect methods are needed for fire

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suppression. According to the results of table 4, the simulated fireline intensity reached 19,153kW/h in plot 1 and 7,737kW/h in plot 2, precluding any direct suppression of the fire's front in the latter. However, the proposed treatments prevent fire from crowning in both plots, retaining it on the surface. In these occasions, the pyric parameters remained at low levels so as to be easily contained by firefighting forces.

A set of "firescale principles" as adapted from Agee and Skinner [50] can be defined (Table 6). Forests treated with these principles will be more resilient to wildfires.

Table 6. Principles of fire resistance for dry forests [51, 52, 53].

Principles	Effect	Advantage	Concerns
Reduce surface fuels	Reduces potential flame length	Control easier; less torching	Surface disturbance less with fire than other techniques
Increase height to live crown	Requires longer flame length to begin torching	Less torching	Opens understory; may allow surface wind to increase
Decrease crown density	Makes tree to tree crown fire less probable	Reduces crown fire potential	Surface wind may increase and surface fuels may be drier
Keep big trees of resistant species	Less mortality for same fire intensity	Generally restores historic structure	Less economical; may keep trees at risk of insect attack

The effectiveness of two of the four proposed principles is assessed in the current research. In plot 1, the low CBD affected fire type and would likely prevent active crowning. However, the dense understory increased available fuel load and resulted to high levels of flame length and intensity. On the contrary, in plot 2 the dense canopy provided the necessary conditions for active crowning since CI factor is low, but the reduced surface load due to thinning, prevent torching of the low canopy parts. In this experimental plot, it is not expected foliar ignition during the early stages of fire as a result of the vegetation characteristics. However, if foliage ignition may occur at some point within the stand, then active crowning is expected.

The simulated silvicultural treatments aimed at the most critical parameters of the two stand structures. In plot 1, clearings reduced surface load significantly and the potential fire could not transmitted to tree foliage. It should be mentioned that in conjunction with a thinning treatment corresponding to 10% of the basal area, forest managers can achieve even milder combustion conditions that would lead to fires that ground firefighting forces can tackle. In plot 2, thinning reduced the available aerial fuel load for combustion so that crown fire would not be sustainable without high wind speeds. However, intensive thinning may result in increased wind-speeds inside stand lowering the fuel moisture content, thus 25% removal of the initial basal area is seems to be effective. Removal of any dead trees, branches and twigs will improve fuel moisture conditions within the stand, while, in final stage planting with deciduous trees will increase foliar moisture content. Pruning of the lowest points of tree crowns (over 3 meters from ground level) is actually unnecessary due to the high levels of CBH. The combination of silvicultural treatments (thinning and clearings) changed the forest

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structure altering the behavior of a potential fire. The results reveal that the fuel treatments had a direct influence upon fire behavior lowering significantly its potential severity.

5. Conclusions

Very few forests will receive fuel treatment over their entire area due to economic constraints. The forest challenge needs to be confronted and where strategic fuel treatment will be more effective at reducing wildfire damage. Simulations help us decide where and how we will apply necessary treatments to forests. The challenges are real, and become more important each year. Mediterranean urban forests continue to burn at unprecedented rates, emplacing undesirable landscape patterns and reducing opportunities for restoration. Our greatest challenge is to expand that scale with socially acceptable treatments to sustain these forests.

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Author Contributions

Theano Samara, Dimitrios Raptis and Ioannis Spanos together conceived and designed the Fuel Treatments and Potential Fire Behavior in Peri-Urban Forests, N. Greece. For the case study, Theano Samara and Ioannis Spanos performed the calculations and Dimitrios Raptis analyzed the data. Theano Samara, Dimitrios Raptis and Ioannis Spanos jointly wrote the paper.

Conflicts of Interest

The authors declare no conflicts of interest.

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