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VEGETATION ANALYSIS AND SILVICULTURAL SUGGESTIONS FOR MITIGATING FIRE DANGER AND PROTECTING NATURE THE CASE OF A NATURA 2000 SITE IN SOUTHERN GREECE

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ABSTRACT

Purpose: The development of a methodological approach for the estimation of the wildfire danger in a protected area, located near a big city, based on the dominant factors contributing to a fire-prone environment and affect fire behavior.

Theoretical framework: Vegetation management in protected areas characterized by sprawling of adjacent urban and suburban development patterns, is a complicated task, especially under Mediterranean climate due to the high vulnerability to wildfires. They should aim, among others, to mitigate forest-fire occurrence risk, eliminate the wildfire damages as well as to protect humans, and conserve the high biodiversity of the protected areas.

Method: We generated a forest fire occurrence danger zone map based on: i) historical fire data ii) types of vegetation and forest ecosystem characteristics, iii) topographical characteristics, iv) distance from the settlements, and v) distance from the roads. A probability model equation for forest fire occurrence was produced. Wildland-Urban Interface mapping was also considered.

Results and conclusion: Four categories of forest fire occurrence danger zones, ranging from very high to low, were classified. The zones with high and very high fire occurrence danger cover a low percentage of the study area (6.84% and 5.76%, respectively). In the very high fire danger zones, *Pinus halepensis* forest and evergreen sclerophyllous vegetation, prevail. A great part of the Wildland-Urban Interface WUI belongs to the zones of high and very high fire occurrence danger.

Research implications: Several silvicultural and policy measures for creating fire-resilient ecosystems and mitigating the possibility of a wildfire occurrence and damages, are suggested.

Originality/value: The determined site-specific vegetation management and policy measures are of great importance for land management in similar areas.

Keywords: Forest Fires, Vegetation Management, Protected Areas, Forest Habitats, Silvicultural Treatments.

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ANÁLISE DA VEGETAÇÃO E SUGESTÕES SILVICULTURAIS PARA MITIGAR O PERIGO DE INCÊNDIO E PROTEGER A NATUREZA O CASO DE UM SÍTIO NATURA 2000 NO SUL DA GRÉCIA

RESUMO

Objetivo: O desenvolvimento de uma abordagem metodológica para a estimativa do perigo de incêndio florestal em uma área protegida, localizada perto de uma grande cidade, com base nos fatores dominantes que contribuem para um ambiente propenso ao fogo e afetam o comportamento do fogo.

Referencial teórico: A gestão da vegetação em áreas protegidas caracterizadas pela expansão de padrões de desenvolvimento urbano e suburbano adjacentes é uma tarefa complicada, especialmente em clima mediterrâneo devido à elevada vulnerabilidade a incêndios florestais. Devem visar, entre outros, mitigar o risco de ocorrência de incêndios florestais, eliminar os danos causados pelos incêndios florestais, bem como proteger os seres humanos e conservar a elevada biodiversidade das áreas protegidas.

Método: Geramos um mapa da zona de perigo de ocorrência de incêndios florestais com base em: i) dados históricos de incêndios ii) tipos de vegetação e características do ecossistema florestal, iii) características topográficas, iv) distância dos assentamentos ev) distância das estradas. Produziu-se um modelo de equação de probabilidade para a ocorrência de incêndios florestais. O mapeamento Wildland-Urban Interface também foi considerado.

Resultados e conclusões: Foram classificadas quatro categorias de zonas de perigo de ocorrência de incêndios florestais, variando de muito alto a baixo. As zonas com risco de incêndio alto e muito alto cobrem uma percentagem baixa da área de estudo (6,84% e 5,76%, respetivamente). Nas zonas de risco de incêndio muito elevado, prevalecem a floresta de Pinus halepensis e a vegetação esclerófila perene. Grande parte da interface Wildland-Urban Interface WUI pertence às zonas de alto e muito alto perigo de ocorrência de incêndio.

Implicações da pesquisa: São sugeridas várias medidas silviculturais e políticas para criar ecossistemas resistentes ao fogo e mitigar a possibilidade de ocorrência de incêndios florestais e danos.

Originalidade e valor: O manejo da vegetação local específico determinado e as medidas políticas são de grande importância para o manejo do solo em áreas semelhantes.

Palavras-chave: Incêndios Florestais, Gestão Vegetal, Áreas Protegidas, Habitats Florestais, Tratamentos Silviculturais.

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1 INTRODUCTION

Natura 2000 Ecological Network of Protected Areas in Europe represents an important step for biodiversity conservation. The network was based on the adoption of the Habitats (92/43/EEC) and Birds (2009/147/EEC) Directives. EU sets specific obligations for all EU Member States for the protection of the wild fauna and flora species as well as for the natural habitat types within the Natura 2000 sites. Greece is recognized as a biodiversity hot spot in the Mediterranean biogeographical region (Georghiou & Delipetrou, 2010), hosting a network of 419 protected Natura 2000 sites, that covers approximately 27% of its national land territory. Many of these protected Natura 2000 sites lay adjacent to big cities e.g., National Park of Parnitha (Athens), National Park of Volvi-Koronia Lakes (Thessaloniki), Panachaiko site, (Patra). It is said that cultures of entire societies can be defined by the type of ecosystem to which a community interrelates, including those related to forest ecosystems (Ritter & Dauksta, 2013; Bardsley et al., 2015). Many people are attracted to reside in forested areas, including

fire prone ones, either forgetting or accepting of the risk (Bardsley et al., 2015). Urban and suburban sprawl towards usually upland forested land creates negative impacts to environment, including habitat fragmentation, water and air pollution, and biodiversity pressures (Concepción, 2021; Alves da Silva et al., 2023; de França Paz et al., 2023).

In these areas, with such major danger from wildfires to human lives, properties, and landscapes, there are ongoing conflicts between urban development within upland areas and vegetation management for its conservation and fire danger mitigation. In protected areas adjacent to urban areas, intense conflicts are also caused because human sprawl and its impacts may conflict with requirements for biodiversity conservation. This is more evident in countries such as Greece, where building outside the urban borders is generally permitted (under a few preconditions). It is referred that among the many human activities that cause habitat loss, the urban development causes some of the greatest local extinction rates and frequently eliminates the large majority of native species (McKinney, 2002; Concepción, 2021).

Recent worldwide wildfires' history shows that these are some of the most damaging and costly on record. Most of them concern wildfires occurring near the cities, within or closed to the wildland-urban interface (WUI) (e.g., 2018 fire in Mati, Greece), that caused high number (102) of civilian fatalities, thousands of homes burned and great damages of human infrastructures. These large fires in urban peripheries create urgent demands for changing vegetation management in peri-urban areas (Bardsley et al., 2015). Additionally, there are many cases, where fire events happen within or closed to protected areas characterized by high biodiversity values, such as the Natura 2000 sites. Description, analytical mapping and fire danger evaluation of areas where forest vegetation is intermixed with settlements or other human infrastructures (WUI), and those lay close to protected areas, are very important and urgent (Colin et al., 1998; Camia et al., 2003; Stewart et al., 2007; Herrero-Corral et al., 2012), due to: i) a great percentage of forest fires occur there, and ii) damages from a possible wildfire are more destructive for human lives and properties (Radeloff et al., 2005a; Radeloff et al., 2005b], and also, there is a high risk of biodiversity loss (Bardsley et al., 2015).

2 THEORETICAL FRAMEWORK

Even though at regional or national scale a wildfire risk estimation is carried out, analytical information and danger assessment at local scale is generally missing, while it is absolute absent for any Greek Natura 2000 site. Studies on wildfire danger and mapping this danger at local scale are very scarce, even in the cases of areas of high danger or valuable areas from ecological or human values point of view. Although it is not easy to precisely predict forest fires, the potential damages of forest fires can be minimized with the help of fire information systems and fire danger mapping (Çolak & Sunar, 2020). This has tragically proved last years in Greece, where 102 people died in 2018 from a wildfire in Mati, Attiki, near to Athens, or 67 people in Peloponnesus in 2007. These two very tragic events, and many others around the world, highlight the great needs for wildfire danger assessment at local scale, which should be followed by the development of appropriate silvicultural and fuel reduction measures for fire-prevention.

Fire occurrence danger analysis at a local scale combined with the collection, analysis, and evaluation of field data, would greatly help to resolve ambiguities about the type of vegetation and prevent potential disasters. For example, recent studies showed that the typical land classification using in fire risk modeling may not effectively help in real fire danger assessment, since land categories of several agro-mixed types of land cover such as "agro-forestry areas" or "land principally occupied by agriculture, with significant areas of natural vegetation" increase fire danger due to the intermixed pattern that favors land vulnerability to wildfires (Ortega et al., 2012], even though they are not included in wildfire typical fuel types.

Palaiologou et al. (2020), also found that among the several land categories favoring fire danger, the olive plantations were predicted to be a substantial contributor to fire exchange among the land cover types by interspersing with conifers, abandoned agricultural lands and grasslands, creating a fuel mosaic with high rates of overall fire spread.

The aim of this study is the development of a methodological approach for the estimation of the static wildfire occurrence danger in Panachaiko Mt. area, a site of the Natura 2000 Network, located near the city of Patra, in southern Greece, in Peloponnesus. As factors that contribute to making a fire-prone environment and affect fire behavior are essential for forest fire danger zone mapping, we generate a probability model equation and a forest fire occurrence danger zone map based on the following data: i) historical fire data ii) types of vegetation and forest ecosystem characteristics, iii) topographical characteristics, iv) distance from the settlements, and v) distance from the roads (Jaiswal et al., 2002). Additionally, the area characterized as Wildland-Urban Interface (WUI) within the study area was determined and mapped. Then, based on our findings, several silvicultural and policy measures for creating fire-resilient ecosystems and mitigating the possibility of a wildfire occurrence and damages, are suggested.

3 METHODOLOGY

3.1 Characterization of the Study Area

The study area is the mountain Panachaiko (southern Greece) and its surroundings (Figure 1). It is laying less than five km east from the Patra city, the third largest Greek city. A great part of the study area (approximately 12,500 ha) belongs to the European Natura 2000 ecological network (code: GR2320007). Administratively, the area belongs to the following five municipalities: Patra, Rio, Erineo, Sympoliteia, Leontio (210,128 inhabitants). It is characterized by moderate and steep slopes, while slopes become gentle in the lower altitudes, near the city of Patra. The altitude ranges from approx. 150 m asl (in the lowest part of the north side of the mountain) up to 1,928 m asl (in the higher mountain peak). The climate of the area, is Mediterranean with an average temperature 17.9 ^{o}C, and annual precipitation 662.7 mm. The dry period, which is crucial for fire events (Ganatsas et al., 2011), lasts for over 4 months, from the middle May to middle September (Figure 2) (meteorological station of Patra, latitude 38^{o} 15', longitude 21^{o} 44'). From the biodiversity point of view, the area hosts 21 types of habitats (according to European Habitat Directive 92/43/EEC), 568 plant species, between them, 63 are Greek endemics and 33 Balkan endemics. There thrive also 155 vertebrates, and specifically 9 amphibians, 26 reptiles, 24 mammals, and 96 bird species, from which 21 are included in the Annex I of the bird Directive 2009/147/EC.



Figure 1 Orientation map showing the study area, in southern Greece.
Source: Produced by the authors.

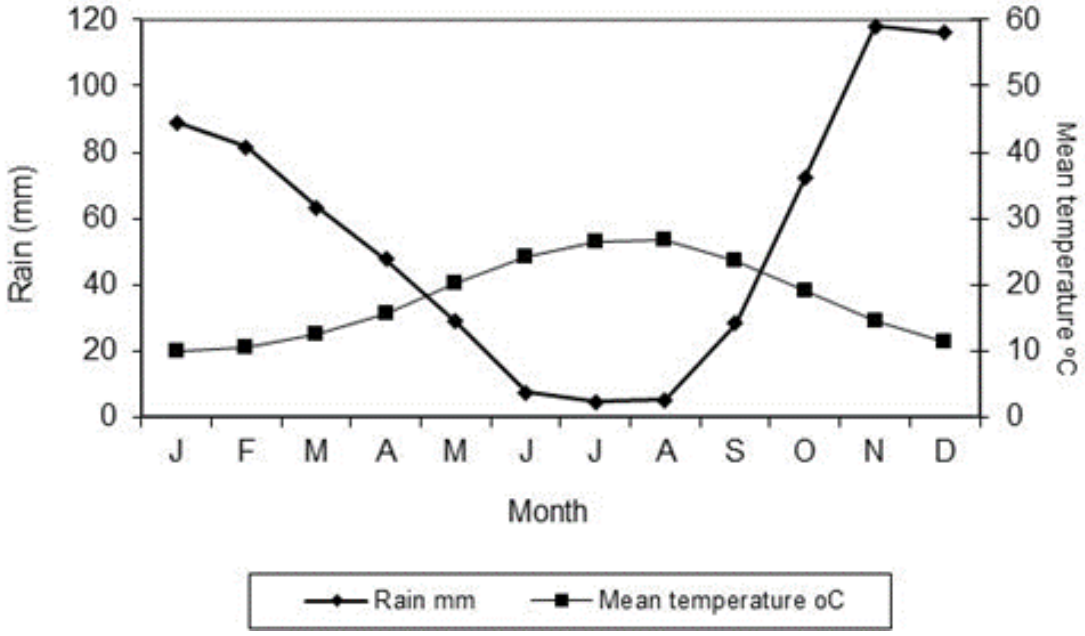


Figure 2 Climatic diagram of the study area.
Source: Produced by the authors.

The vegetation of the area, according to the CORINE land cover (CLC) nomenclature, is characterized by a mosaic of different types, including 15 types which belong to different land cover classes, from agricultural land to high forests (Figure 3). Among them, the Sclerophyllous vegetation, Transitional woodland-shrub, Land principally occupied by agriculture, with significant areas of natural vegetation, and Coniferous forest, cover the largest area: 27.01%, 16.59%, 11.60%, and 8.33 % respectively (Table 1). Within the site of Natura 2000 network, a wide range (21) of habitat types were recorded (Figure 4), while four of them

are pure high forest habitats. The vegetation types distributed in the lower altitudes, that of *Quercetalia ilicis* zone are fire-adapted/fire-tolerant ecosystems e.g. *Pinus halepensis* forests and sclerophyllous vegetation of evergreen broadleaved species (with *Quercus coccifera* and *Qurcus ilex* as dominant species), while those at higher altitude such as fir (*Abies cephalonica* Loudon) forest, or *Juniperus* species shrubland belong to non-adapted to fire ecosystems (Ioannidis et al., 2021). According to the archives of the Fire Brigade Department and the Local Forest Service, wildfires are very common phenomenon in the area, especially in the lower zone (total number events 96, during the reference period).

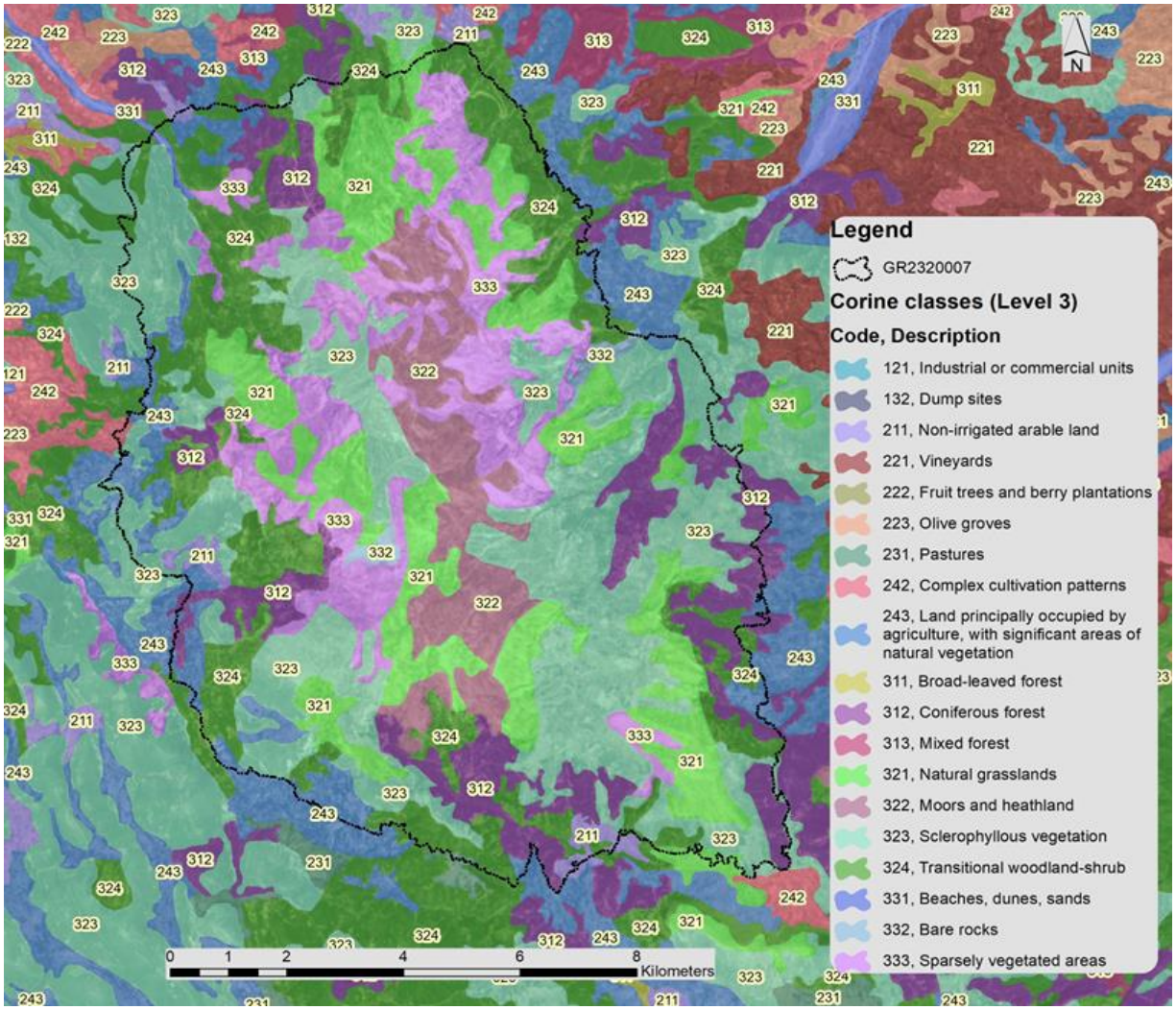


Figure 3 Map of CORINE land cover classes (Level 3) for the study area. GR232007 is the code site of Natura 2000 network.
Source: Produced by the authors.

Table 1 Surface and coverage percentage (%) of each CORINE land cover class in the study area.

Corine 2018 Classes (Level 3)	Description	Area (ha)	Percentage (%)
112	Discontinuous urban fabric	79.72	0.23
121	Industrial or commercial units	255.49	0.73
122	Road and rail networks and associated land	7.40	0.02
132	Dump sites	29.67	0.09
211	Non-irrigated arable land	600.23	1.73
221	Vineyards	1358.94	3.91
222	Fruit trees and berry plantations	202.00	0.58
223	Olive groves	526.34	1.51

231	Pastures	400.70	1.15
242	Complex cultivation patterns	1866.53	5.37
243	Land principally occupied by agriculture, with significant areas of natural vegetation	4033.68	11.60
311	Broad-leaved forest	154.13	0.44
312	Coniferous forest	2897.59	8.33
313	Mixed forest	1331.65	3.83
321	Natural grasslands	2417.16	6.95
322	Moors and heathland	1163.05	3.34
323	Sclerophyllous vegetation	9395.01	27.01
324	Transitional woodland-shrub	5770.49	16.59
331	Beaches, dunes, sands	362.88	1.04
332	Bare rocks	82.34	0.24
333	Sparsely vegetated areas	1846.54	5.31
	TOTAL	34781.52	100

Source: Produced by the authors.

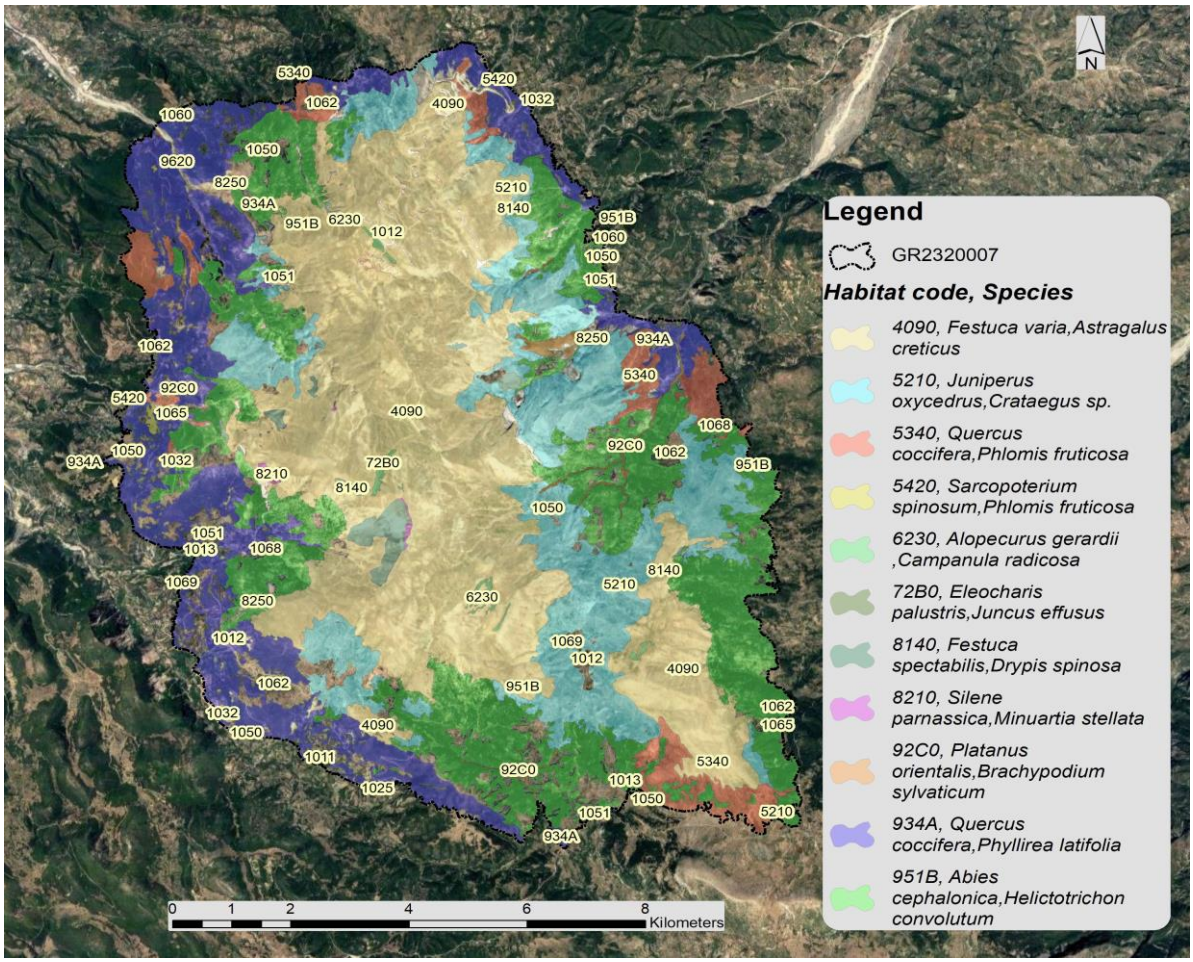


Figure 4 Map of the habitat types within the Panachaiko Site of Natura 2000 network, according to the Habitat Directive 92/43. No vegetated habitat types are omitted.
Source: Produced by the authors.

3.2 Assessment and Mapping of Wildfire Occurrence Danger

The fire proneness of any area depends on many factors with most important: vegetation characteristics (type, density, crown closure, developmental stage), environmental factors (humidity of the area, winds, topography) and human presence (proximity to settlements,

distances from roads, etc.) (Sivrikaya et al., 2014). For the assessment of fire occurrence danger, the following procedure and factors were taken into consideration and the methodology was based on that of Jaiswal et al. (2002), and Erten et al. (2004).

3.2.1 Types of vegetation

For the area inside the Site of Natura 2000, the distribution of vegetation types according to the habitat mapping was considered. For the other area, the cartographic data of the Corine Land Cover were taken from the Corine database. In both areas, authors visited repeatedly the study area for confirmation the vegetation types. Based on the above data, a vectorial polygonal information level was created for the area. According to this, each polygon of the area took a code Nxxxx (four-digit) according to the codes of habitat Directive 92/43/EEC for the polygons inside the Site, or Cxxx (three-digit), according to the Corine codes of land cover for the polygons outside the Site.

3.2.2 Topography

A Digital Elevation Model (DEM) was created from the isolines of 10 m, with a cell size of 10 m. Afterwards, the mean altitude for each polygon was computed.

3.2.3 Distance from the settlements

The settlements were digitized based on the Three band (RGB) high resolution Orthophotographs (0.25 m spatial resolution) of the year 2015 provided from "Hellenic Cadastre", then for each polygon (cell size of 10 m), the mean distance from settlements were computed.

3.2.4 Distance from the roads

The roads were digitized based on the color Orthophotographs available in the site "Hellenic Cadastre" (http://gis.ktimanet.gr/wms/ktbasemap/default.aspx). Then, for each polygon (cell size of 10 m), the mean Euclidean distance from the road network was computed.

3.2.5 Historical fire events data

Historical fire occurrence data (Jaiswal et al., 2002) derived from the archive of local Forest Service. for the period 1990–2020. The exact points of fire events were positioned in the map of the area. Historical fire data collected concern the date of fire event, type of ecosystem occurred, and the area burned.

3.3 Vegetation & Silvicultural Analysis

To determine which ecosystem corresponds to the CORINE codes, we repeatedly visited the study area, and we recorded the type of ecosystem for each polygon, and the dominant forest tree and shrub species were also recorded. Finally, in the areas which were found to belong to very high fire occurrence danger zone, five sample plots of 500-m2 (20 m X 25 m) were taken in each vegetation type, within which the mean tree height and canopy cover were measured, and the composition of wood species as well as the dominant species, were recorded.

3.4 Statistical Analysis

Spatial statistical analysis was carried out in R environment, to identify the environmental factors, human factors and types of vegetation that affect the wildfire danger. A Multinomial logistic regression model was selected for the final statistical analysis, even though several linear and non-linear models were tested (Oikonomakis & Ganatsas, 2020). The output was the possibility ($p<0.001$) of fire occurrence in any point (cell size of 10 m), in the studied area. All the above data were analyzed and correlated with the historical fire occurrence data (Roloff et al. 2005) derived from the archive of local Forest Service. Afterwards, mapping of the wildfire occurrence danger was produced.

3.5 Mapping of the Wildland-Urban Interface – WUI

For the mapping of the Wildland-Urban Interface – WUI in the area, we took into consideration the cartographic data relevant to vegetation type and settlements (Colin et al., 1998). Specifically, the method applied is deployed in the following steps: i) Record of settlements, human infrastructures, and isolated houses that are in a distance less than 200 m from natural vegetation. ii) Creation of a buffer zone of 100 m width, from the settlements previously recorded. These areas are considered as Wildland-Urban Interface (WUI) (Lampin-Maillet et al., 2009). Then a map analysis was made for the estimation what part of the WUI area belongs to each category of the predicted fire danger.

4 RESULTS AND DISCUSSION

4.1 Assessment the Fire Occurrence Danger in the Area

Among the several statistical models tested, the logistic regression was selected, since it showed the best fitting, according to the applied statistical criteria. More specifically, the Variance Inflation Factors (VIFs) were calculated, and all the independent variables were tested through multiple regression models. As in other studies, a cutoff value > 10 was selected to select the best models (Oikonomakis & Ganatsas, 2020). The equation expressed the estimation of probability ($p<0.001$) of fire occurrence was the following:

$$K = \frac{\exp(Z)}{1+\exp(Z)}$$

Where:

K is the probability of fire occurrence

The value of Z was estimated by the following equation:

Z = 0,179 - 0,002 DR - 0,0001DS - 0,0026A - 17,513VTC112 - 18,857VTC121 - 18,389VTC211 - 19,703VTC221 - 18,841VTC222 - 19,728VTC223 + 0,892VTC242 + 0,396VTC243 + 0,498VTC244 + 0,480VTC312 + 2,0189 VTC313 - 17,178VTC321 - 18,781VTC322+ 0,643VTC323 - 0,575VTC324 - 0,550VTC331 - 16,973VTC332 - 16,708VTC333 - 18,688VTN1020 - 18,153VTN1021 - 17,769 VTN1050 - 15,435VTN4090 - 17,437VTN5210 + 0,051VTN5340 - 18,143VTN5420 - 14,670VTN6230 - 16,258VTN8140 - 17,665VTN8210 - 18,254VTN8250 - 16,329VTN92C0 - 0,520VTN934A

Where:

DR is the mean distance of a point from the roads
DS is the mean distance of a point from the settlements
A is the mean altitude
VTCxxx is the presence of the vegetation type according to CORINE land cover type xxx, for the areas laying outside the Natura 2000 site
VTNxxxx is the presence of the habitat type according to habitat directive 92/43, inside the area of Natura 2000 site. xxxx (NATURA).

Afterwards, for each point of the studied area, the fire occurrence danger was assessed, and the danger map was created (Figure 5), showing the probability of fire occurrence in each point. For functional reasons, the values of K, were classified in four fire danger classes: low, medium, high, and very high danger, according to international practice (Jaiswal et al., 2002)], as below, and the area occupied by each class is depicted in Table 2.

- Low danger (areas with possibility of fire occurrence 0%-20%),
- Medium danger (areas with possibility of fire 20%-40%),
- High danger (areas with possibility of fire 40%-60%),
- Very high danger (areas with possibility of fire 60%-80%).

Among the parameters entered in the equation, there are 31 vegetation types that contribute to either increasing the fire occurrence danger (VTI) or decreasing fire occurrence danger (VTD). If we replace in the above equation the sum of these two groups of vegetation, the equation takes the following form, where the coefficients of the two vegetation groups are the sum of coefficient of the vegetation types inserted in the equation either increasing or decreasing the fire occurrence danger, since all the variables are in the form presence/absence, and thus, they are equivalent in their weight.

$$Z = 0{,}179 - 0{,}002DR - 0{,}0001DS - 0{,}0026A + 4.98VTI - 266.44VTD$$

The above equation can take the general form:

$$Z = a - bDR - cDs - dA + eVTI - fVTD$$

Where:

a,b,c,d,e,f are coefficients of the equation. This general from can be applied in other similar fire prone areas after testing in the specific site conditions of each area.

The analysis of the data presented in the Fire Occurrence Danger Map (Figure 5), shows that the “Very high danger” zone, where there is an urgent need to take preventive wildfire measures to mitigate fire occurrence, occupies only a small part of the area, 1,197.8 ha (5.76% of the total area) (Table 2). The great part of the area (70.36%) belongs to the “Low danger zone”. Also, it must be pointed out that, even though the entire area in-side the site of Natura 2000 network belongs to the “Low danger zone”, there are some points in the north side of the Site that are tangential with areas of “Very high danger”. Thus, despite a fire event is not expected to be happen within the Site, it has a high possibility to enter into Site. Fire spreading among the different land uses is observed in many cases (Palaiologou et al., 2020), e.g., in Parnitha National Park, (Greece), when a wildfire transmitted from low land to the upland Greek fir forest and destroyed half of the forest. The fire danger model, developed in our study, it expresses both the likelihood of ignition as well as the probability of fire occurrence in the study area, since both parameters greatly were influenced by the factors tested (vegetation type,

topography, human presence). Our findings agree with reports from other studies (Jaiswal et al., 2002; Sivrikaya et al., 2014; Ganteaume et al., 2011; Blauw et al., 2017). Similar distribution of fire danger classes was found by Sivrikaya et al. (2014) for a forested area in Turkey with *P. brutia* as dominant tree species. However, they reported a greater rate for the area of extreme (very high) fire occurrence danger (11.6%), a quite expected value since the referred area belongs almost entirely in the low floristic zone. Similarly, Jaiswal et al. (2002) in India, who followed a similar approach, reported higher values for both "very high danger" and "high danger" classes (20% and 10%, respectively), due to the dry and dense forest consisting of *Shorea robusta*, baboo and dry mixed species, is more susceptible to fire.

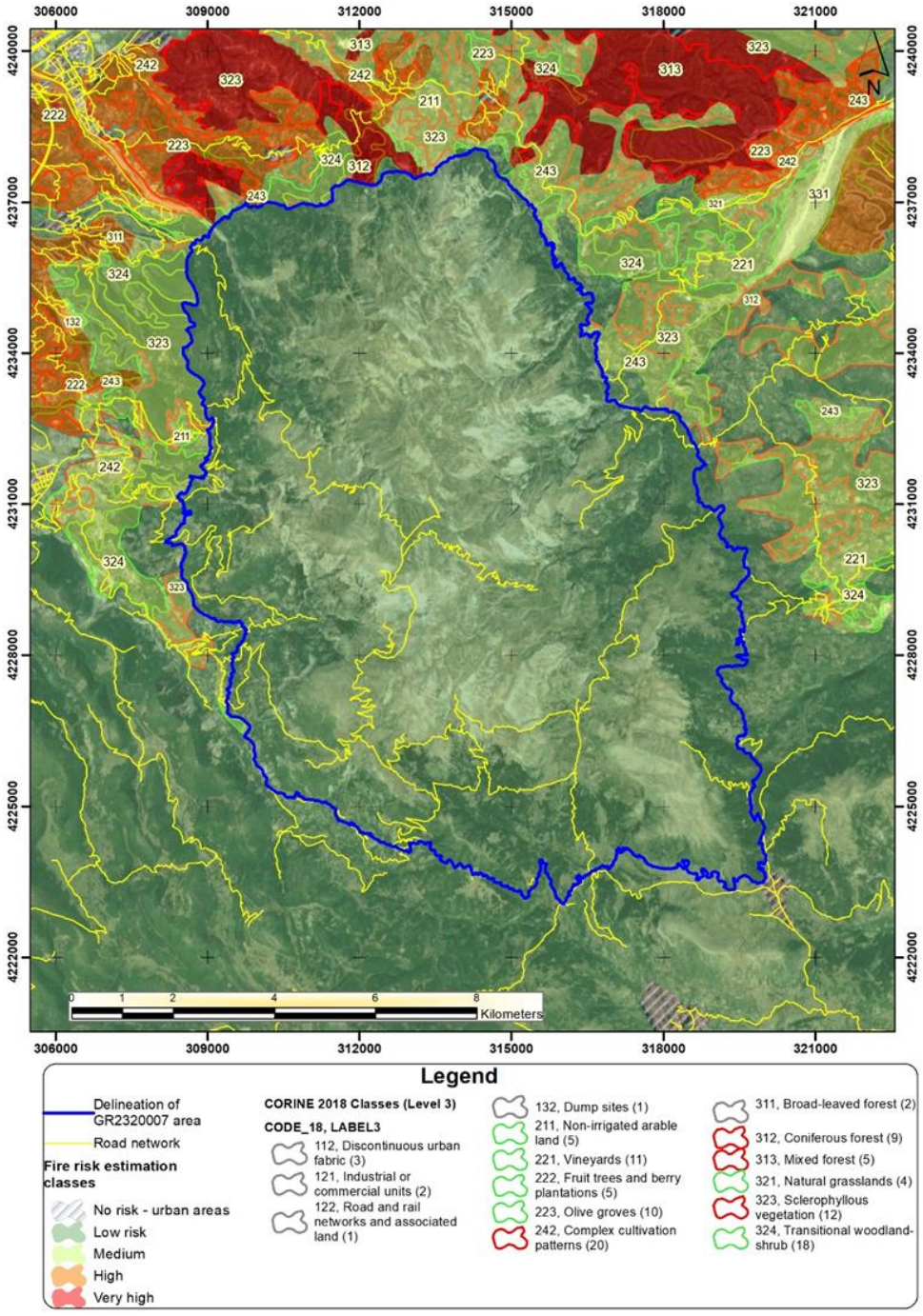


Figure 5 Map showing the fire occurrence danger in the studied area, as well as the CORINE land cover classes exist within the danger classes.
Source: Produced by the authors.

Table 2 Extent of fire occurrence danger zones in the study area of Mt. Panachaiko, southern Greece.

Fire Occurrence Danger	The entire study area		Site of Natura 2000 network	
	Area (ha)	%	Area (ha)	%
Low danger (0%-20%)	23,921.64	70.36	12,500	100
Medium danger (20%-40%)	5,796.22	17.05	0	0
High danger (40%-60%)	2,324.32	6.84	0	0
Very high danger (60%-80%)	1,957.82	5.76	0	0
Total	34,000.00	100.00	12,500	100

Source: Produced by the authors.

4.2 Factors Affecting the Fire Occurrence Danger

Analyzing the selected model, and the variables included in the equation, we can see that the following factors greatly affect the probability of fire occurrence in the study area:

4.2.1 Environmental factors

4.2.1.1 Altitude

The fire danger decreases with increasing altitude. All places with high altitude, over 800 m asl, belong the low fire occurrence danger zone, while areas at low altitude belong to the high or very high fire occurrence danger zone. This is a result of climate influence, since it is well recognized the relationship of land elevation with temperature and precipitation, the higher elevation the lower temperature and higher precipitation. Both contribute to reducing summer dry period and increasing vegetation moisture, which are key factors for fire danger reduction (Ganatsas et al., 2011).

4.2.1.2 Human Presence

Distance from roads and settlements is important factor influencing the fire occurrence. Human settlements and roads/footpaths inside or near the forest, are considered sources for the fire initiation. Data analysis from the current study strongly supports that the shorter the distance of the forest from the road or from settlements the higher fire danger. That means that when humans easy access in a specific area, this increases the fire occurrence danger for the area. Thus, a high wildfire occurrence danger is associated to human intervention and presence, i.e., proximity (short distance) to roads and settlements (Jaiswal et al., 2002; Jain et al., 1996; Ganteaume et al., 2013). Our results concur with other studies that have studied in detail the role of transportation networks and human presence as a source of fire ignitions (Gralewicz, 2010; Ortega et al., 2012). Especially, a distance of less than 500 m from the urban areas, or from the main roads was found to be very suspicious for fire ignitions (Catry et al., 2007).

4.2.1.2 Types of Vegetation

A series of vegetation types were entered to the model equation, either those of CORINE land cover classes, as well as the habitat types according to habitat Directive that concern the area included in the Site of Natura 2000 network. Most of the vegetation types prevailing at the lower altitude, increase the fire occurrence danger, while a few of them reduce the possibility for fire occurrence (Figure 5). Based on statistical analysis, six vegetation types that entered in the model equation (1) increase the fire occurrence danger. This group mainly concerns forests and wild vegetation (CORINE Land Cover codes 312, 313, 323), and a small percentage of mixed agro-wild vegetation areas (Corine codes 242, 243, 244), (Table 3). Within the Site of

Natura 2000 network, the only habitat type increases the prob-ability of fire is 5340: Garrigues of Eastern Mediterranean, that is dominated by the species *Quercus coccifera*, an evergreen oak species (Table 4). On the other hand, seven vegetation types, from CORINE land cover classes, entered in the equation model decrease the fire occurrence danger (Table 3); this concerns: i) Permanent agricultural crops such as the types: Non-irrigated arable land (211), Vineyards (221), Fruit trees and berry plantations (222) and Olive groves (223), ii) wild types of vegetation of low biomass accumulation such as Natural grasslands (321), Moors and heath-land (322) and Transitional woodland-shrub vegetation type (code 324). Within the Site of Natura 2000 network, the presence of the following habitats decreases the probability for fire occurrence danger (Table 4): habitat types: Urban (Settlements) 1050, Cropland 1020, 1021, all the types with low vegetation 4090, 5210, 5420, 6230, 8140, 8210, 8250, and the hygrophilous forest type 92C0 dominated by *Platanus orientalis*. It is interesting that among the vegetation types that reduces the fire danger is the high forest of low canopy density with *Quercus coccifera* trees 934A.

Thus, we can distinguish three categories of vegetation types, those that increase the fire danger, those decrease fire danger and those do not affect fire danger. The first category concerns mainly wild woody vegetation such as forests, woodlands, and wild vegetation (e.g., pure *P. halepensis* forest, mixed forest with *P. halepensis* and evergreen Mediterranean oaks, and sclerophyllous vegetation). These types of forest ecosystems are generally characterized by the accumulation of highly flammable biomass that increase the fire danger occurrence (Ganteaume et al., 2011; Koutsias et al., 2012). This kind of vegetation is also the dominant vegetation in the *Quercetalia ilicis* floristic zone which is extensively distributed along the Mediterranean region and in which most forest fires occur every summer (Goudelis et al., 2008). It is interesting that the high fire danger category also includes several mixed types of land cover such as "agro-forestry areas" (code 244), "complex cultivation patterns" (code 242)," land principally occupied by agriculture, with significant areas of natural vegetation" (code 243). These land types of diverse landscapes with intense human impact (high road density, human presence, etc.) seem to increase fire danger due to the intermixed pattern that favors land vulnerability to wildfires (Ortega et al., 2012). On the other hand, there are vegetation types that contribute to the fire occurrence reduction. These vegetation types are found either in areas regularly visited and monitored by growers to protect their crops i.e., the permanent agricultural crops (non-irrigated arable land, vineyards, fruit tree and berry plantations, olive groves), or in areas where the dry biomass accumulation of wild vegetation is very low, i.e., natural grasslands, heathland, transitional woodland-shrub vegetation.

Table 3 CORINE land cover classes (level 3) and their influence on the probability of fire occurrence danger, in Mt. Panachaiko, southern Greece.

Classes increasing fire danger	Classes decreasing fire danger	Neutral
Complex cultivation patterns (code 242) Land principally occupied by agriculture, with significant areas of natural vegetation (code 243) Agro-forestry areas (code 244) Coniferous forest (code 312) which concerns *Pinus halepensis* forests in the study area Mixed forest (code 313) Sclerophyllous vegetation (code 323)	***i) Permanent agricultural crops such as the types:*** Non-irrigated arable land (211) Vineyards (221) Fruit trees and berry plantations (222) Olive groves (223) ***ii) Wild types of vegetation of low biomass accumulation such as:*** Natural grasslands (321) Moors and heathland (322) Transitional woodland-shrub vegetation type (code 324)	Pastures (231) Sparsely vegetated areas (333)

Source: Produced by the authors.

Table 4 Habitat types, according to Habitat directive, and their influence on the probability of fire occurrence danger, in Mt. Panachaiko, southern Greece.

Habitat types increasing danger	Habitat types decreasing danger	Neutral
5340 Garrigues of Eastern Mediterranean, dominated in the studied area by the species *Quercus coccifera*	Urban (Settlements) 1050, Cropland types 1020, 1021, All the types with low vegetation 4090, 5210, 5420, 6230, 8140, 8210, 8250, The hygrophilous forest type 92C0, dominated by *Platanus orientalis.* The high forest of low canopy density with *Quercus coccifera* trees 934A	951B *Abies cephalonica* forests 72B0 Rush meadows vegetation, dominated by *Juncus* species

Source: Produced by the authors.

The forests and the wild vegetation types cover the great percentage (88.8%) of the very high fire danger zone (Table 5). Mixed forests (code 313) consisting of *Pinus halepensis* and evergreen broadleaved species (*Quercus coccifera, Quercus ilex, Arbutus adrachne and A. unedo, Phillyrea latifolia*) cover the greater part (42.31%) of the very high danger zone. The coniferous forest, dominated by the tree species *P. halepensis*, covers 8.61% of this zone. This forest characterized by pure Aleppo pine stands, with an understorey of evergreen sclerophyllous shrubs, and extents from sea level to an altitude of 800 m asl. According to the field measurements, the average tree height of *P. halepensis* is 14.5 m, with an abundant tall woody shrub layer of an average height of 3.2 m. The Sclerophyllous vegetation, dominated by the species Q. *ilex, Q. coccifera, Pistacia terebinthus, A. adrachne, Ph. latifolia, A. unedo, Erica manipuliflora*, *Pistacia lentiscus*, presents a mean height 2.8 m, with a dense canopy (over 90%), cover 37.92% of the very high danger zone. Finally, a small part belongs to the agriculture land intermixed with wild vegetation (7.67%).

Table 5 Vegetation and silvicultural characteristics of land types increasing the wildfire occurrence danger.

Vegetation type	Area occupied within the high fire danger zone (ha)	(%)	Mean Canopy cover (%)	Mean Height of dominant species (m)	Dominant tree Species	Other woody species
Coniferous *Pinus halepensis* forest (code 312)	169.4	8.61	78.1	14.5	*P. halepensis (*overstory)	*Q. coccifera, Q. ilex, A. adrachne A. unedo, P. latifólia.*
Mixed forest (code 313)	832.6	42.31	90.2	13.2	*P. halepensis* (overstory)	*Q. coccifera, Q. ilex, A. adrachne A. unedo, P. latifólia.*
Sclerophyllous vegetation (code 323)	746.1	37.92	85.4	2.8	*Q. coccifera, Q. ilex, A. Adrachne*	*P. terebinthus, Ph. latifolia, A. unedo, E. manipuliflora, P. lentiscus*
Intermixed Agro-forestry areas (codes 242,243,244)	150.9	7.67				

Source: Produced by the authors.

4.3 Mapping of the Wildland-Urban Interface – WUI

By the application of the cartographic method described above, we produced the map showing the distribution of the zone Wildland-Urban Interface in the studied area (Figure 6). WUI covers a total of 3,641.02 ha (10.71%). While it is interesting that a great part of this zone 1,057.03 ha belongs to the categories of high and very high fire danger (Table 6). This means that over half (54.0%) of the studied area assessed to the category of high and very high danger,

belongs to WUI. This WUI zone is distributed in the lower altitudinal area, and lays outside the site of Natura 2000 area. This area should be considered of high priority for taken ap-propriate fire prevention measures in order to reduce the fire danger as well as to mitigate the impacts form any possible fire events. Thus, fire prevention measures should be focused on the WUI area as a matter of high priority. Herrero-Corral et al. (2012), found that wildfire incidence (number of fire events and area burned) is higher among isolated houses and small groups of structures than in housing estates or towns, in the WUI area of Madrid.

Table 6 Area characterized as WUI and belongs to the category of high wildfire occurrence danger.

Category	Area occupied (ha)	Proportion of the total area (%)	Occupation of the "very high and high danger" category (%)
WUI within the study area	3.641,02	10.71	
Part of WUI that belongs to category of high and very high wildfire danger	1.057,03	3.11	53.99

Source: Produced by the authors.

4.4 Silvicultural and Policy Measures for Creating Fire-Resilient Ecosystems

Land management in areas with a mosaic of land uses such as the studied area, is a difficult task. Prior to implementation of any measures to decrease the danger of wildfires, their impacts on people and biodiversity should be considered. Depending on the scale and scope of the activities, any changes in vegetation management aiming at fire danger mitigation, such as fire prevention-silvicultural measures (e.g., thinning, clearings), should be combined with biodiversity conservation policy (Bradstock & Gill, 2001; Bardsley et al., 2015). However, a lot of work done worldwide in determining specific fire preventions measures that can reduce fire danger without reducing biodiversity values (Agee & Skinner, 2005; Stephens & Moghaddas, 2005). It is suggested that when planning pre-fire prevention measures, it is better design a strategically multiple treated stands across the landscape (Finney et al., 2005; Galiana-Martín, 2017), while computer modeling can help in planning in which part of the landscape to apply hazard fuel reduction treatment (Roloff et al., 2005; Ager et al., 2014).

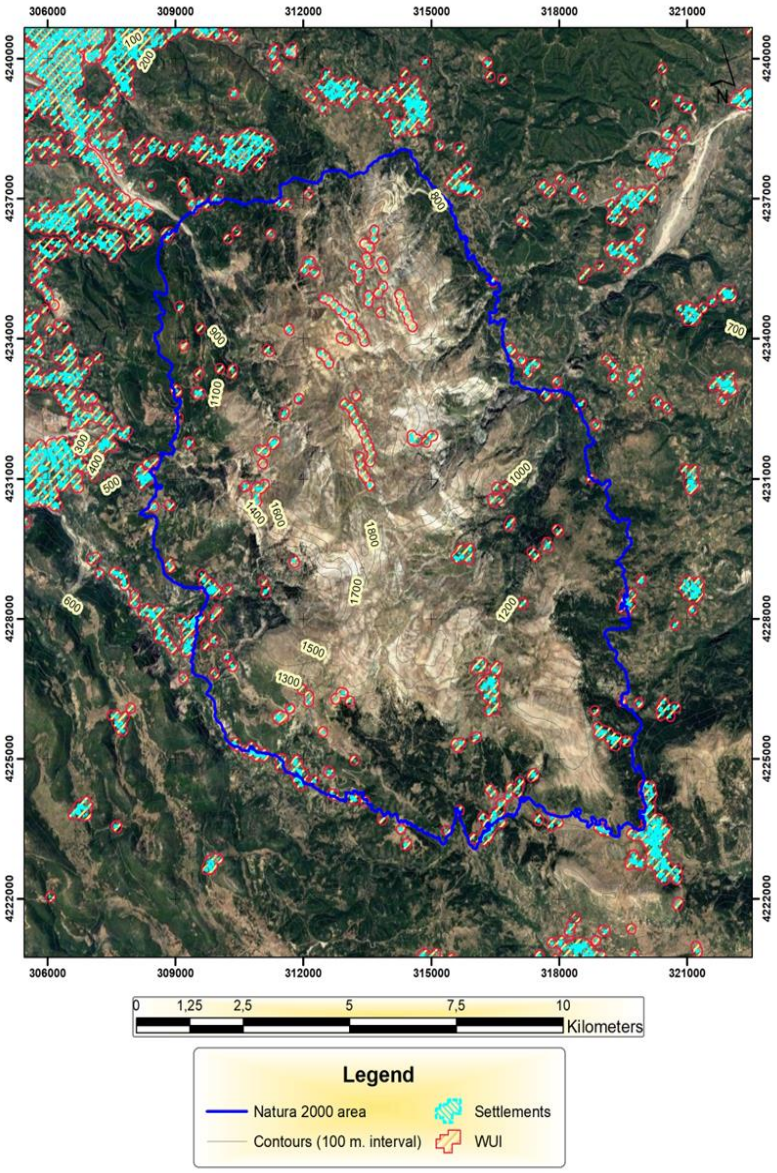


Figure 6 Mapping of the Wildland-Urban Interface – WUI.
Source: Produced by the authors.

Fire prevention treatments should be focused on ecosystems and vegetation types that data analysis showed that they increase the fire occurrence danger. Based on a computer modeling, it is ideally suggesting that a random pattern of different fuel treatments at more than 15% to 20% of the target area, is considered necessary for starting the restriction of fire movement (Finney, 2007). This percentage could be lower if the treatments are oriented specifically to impede fire movement. Increased treated area further reduces potential spread. Palaiologou et al. (2020), found that fuel treatment effective-ness was achieved with an optimized allocation of treatment units with an area greater than 200 ha for an area with similar land cover characteristics to the study area (Mytilini island, Greece). They suggested, for their studied area, that future work should focus on cooperative landscape fuel management of olive groves and forested areas to create an *Olea–Pinus* landscape fuel management strategy that includes multiple adjacent treatments that cross vegetation type boundaries. The intensification and support of traditional land use practices provides an opportunity to reduce danger more efficiently with limited resources. These suggestions may suit to our case since the lower part of our studied area resembles to their studied area. However, the suggested fire prevention

treatments may come to contrast to the re-quirements from the forest management in the area, as well as for the biodiversity conservation in the protected area. The problem of conflicting vegetation management goals, which must plan for both biodiversity conservation and wildfire danger mitigation, has intensified after recent major wildfires in and around metropolitan centers (Bardsley et al., 2015). Based on the data obtained from the determination of the fire danger, the following fire prevention measures are proposed:

4.5 Suggested Silvicultural Interventions

Fire protective management should focus in priority on these types of ecosystems increasing fire danger. However, due to the demands for nature conservation, any restriction of the distribution of the existed ecosystems should be avoided. Thus, forest vegetation management through the appropriate silvicultural treatments that contribute to reducing the fuel amount, while maintaining high biodiversity and resilient ecosystems should be carefully designed (Stephens & Moghaddas, 2005):

- For pure *P. halepensis* forest stands (code 213) and mixed (*P. halepensis* and Mediterranean Oaks) forest stands (code 313), pruning and thinning from below (Keyes & O'Hara, 2002; Piqué et al., 2022; Ganatsas et al., 2022) should be applied, at least within the areas belonging to very high fire danger zone, and within WUI, as well as around the human infrastructure. This aims at the increase height to live crown and will reduce the average canopy bulk density. The stand's thinning should not exceed the 20% of the initial basal area, so as not to reduce the tree crown density too much, otherwise this will contribute to the increase of surface wind and the fuels will be drier (Agee & Skinner, 2005). Piqué et al. (2022), pointed out that pre-commercial *P. halepensis* stand thinning, when accompanied with pruning and surface fuel management, had a clear impact on fire behavior and on the potential of fire crowning during the first two to four years after the interventions.
- For Sclerophyllous vegetation (code 323), and the habitat type (5340) Garrigues dominated by *Q. coccifera*, selective shrubland clearing would be the most appropriate treatment (Baeza et al., 2005), in combination with pruning, and thinning in area occupied by dense thickets. All these treatments aim at reducing fuel mass.
- For the intermixed agro-forestry areas (Complex cultivation patterns (code 242), Land principally occupied by agriculture, with significant areas of natural vegetation (code 243), Agro-forestry areas (code 244), mechanical clearings of the wild vegetation are suggested, to reduce fuel mass.
- Complementary plantings, mainly with native broadleaved fire-resilient species of the *Quercetalia ilicis* floristic zone (e.g., *Pistacia lentiscus, Olea europaea var. sylvestris, Spartium junceum* (Molina et al., 2017; Molina et al., 2019) in the zones of very high and high fire occurrence danger, within WUI and as landscaping hedges in the WUI and on both sides of local roads, can further help to reduce wildfire occurrence and to foster the development of resilient forest ecosystems.
- Finally, prescribed fire even though is suggested as an effective treatment option, it cannot be performed in Greece because it is not allowed by the Law.

4.6 Policy Measures

Policy tools and actions that can increase the effectiveness in mitigating potential fire behavior are proposed below:

- Improvement of the existed forest road network to provide accessibility and access of firefighting vehicles, etc., mainly in high fire danger areas.

- Seminars for the staff of the Fire Service with the special conditions of the area (vegetation, habitats, value of the area, high danger zones and WUI, topography, relief, road network and its accessibility, network of water intake points and its adequacy, etc.).
- Preparation of settlement evacuation plans for each Municipality and testing their implementation.
- Placing information signs on high-traffic roads passing through high-danger areas, as well as at intersections of the main forest road network.
- Construction of fire outposts and additional water reservoirs for fire protection, in "high danger" areas and near roads that provide easy access to fire trucks, after analysis and evaluation of the spatial distribution and the characteristics of the water intake network.

5 CONCLUSION

Research findings show that the developed methodology concluded to the determination of high and very high-danger zones of fire occurrence, where immediate precautionary measures are required to reduce fire danger. This zone occupies a relatively small area in Mt. Panachaiko (1,197.8 hectares - 5.76% of the total area) and is located outside the area of the NATURE 2000 network. It also estimated that the total area of the WUI amounts to 3,641.02 hectares, of which 1,057.03 hectares belong to the areas of high and very high danger of fire. In these areas, precautionary measures are required as a priority, to reduce the danger of a fire and minimize the impacts. Many areas of Natura 2000 network are in the same condition. These areas could be studied with similar or more sophisticated ways for fire danger assessment and consequently special fire prevention measures must be taken for each case, to avoid fire consequences to human lives and properties and to conserve biodiversity. Global warming and other climatic factors which continuously change, and can affect future wildfire occurrences, should also consider.

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