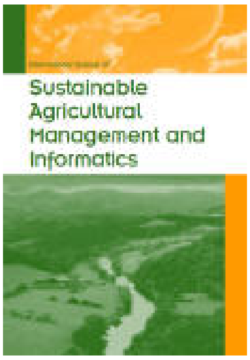

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Evaluation and enhancement of accessibility of forest areas through the road network for conducting firefighting operations via GIS and fire susceptibility analysis

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Abstract: Managing wildfires relies on comprehensive prevention studies and decision-making plans, with the forest road network serving as the primary means for ground firefighting forces. This research establishes a multi-criteria assessment and improvement system for forest areas accessibility, enhancing firefighting operations. Criteria like hiking time, distance from the road network, and terrain topography determine accessibility. Using the analytical hierarchy process (AHP) and spatial analysis considering slope, aspect, fuel type, and distances from human infrastructure, high fire risk areas are identified. This insight led to designing new roads in critical zones to enhance firefighting effectiveness. Re-evaluating accessibility post-road design demonstrates the percentage improvement achieved. Applied in mountainous, mid-altitude, and suburban Mediterranean forest ecosystems, this methodology offers guidelines for real-world forest management, enhancing the sustainability and resilience of forest ecosystems.

Keywords: forest firefighting; wildfire prevention; forest roads planning; decision support system; analytical hierarchy process; AHP; multicriteria analysis.

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1 Introduction

Mediterranean forest ecosystems are increasingly susceptible to the phenomenon of forest fires (Dimitrakopoulos et al., 2011; Moreira et al., 2020; Ganteaume et al., 2021; Tedim et al., 2015). The Mediterranean region is particularly vulnerable to these fires due to a unique combination of climatic conditions, characterised by dry and hot summers, along with the presence of fire-prone vegetation (Mitsopoulos et al., 2020; Bacciu et al., 2021). Greece is one of the countries consistently affected by forest fires. Every year, vast forest areas are engulfed in flames, leading to significant ecological challenges, property and infrastructure losses, and even the loss of human lives (Evelpidou et al., 2022).

The need to address forest fires has led to the implementation of prevention and firefighting studies (Chuvieco et al., 2023; Ferreira et al., 2015). Many researchers (Gonzalez-Olabarria et al., 2019; Fernandes et al., 2016; Martel 2015; Barmpoutis et al., 2020) focus on evaluating the factors contributing to fire occurrence and designing suppression systems. Fire suppression can be divided into two main methods:

a aerial methods, which involve firefighting aircraft (Zhou et al., 2022)

b ground methods, mainly consisting of vehicles and ground teams that wet the fire (Zhdanova et al., 2018) and utilise earthmoving machinery to clear vegetation and create firebreaks (Plucinski, 2019).

The use of aerial firefighting systems is essential due to the topography, terrain, and conditions where ground methods might face challenges in approaching fires. However, aerial methods do not always provide complete extinguishment; they control and limit fire progression (Volkov et al., 2017; Yuan et al., 2015). Effective fire suppression needs to be achieved at the onset of the fire before it transforms into an uncontrolled blaze (Chen et al., 2023; Collins et al., 2018). Given the time required for fire detection and planning, aerial methods attract the fire after the critical window, when the fire has already spread.

Ground firefighting methods are crucial tools in the effort to confront and extinguish forest fires before they cause significant damage to forests and natural ecosystems (Laschi et al., 2019). However, the effectiveness of ground operations is directly linked to the existence, condition, and spatial distribution of road networks, which provide access to forested areas (Jazebi et al., 2020).

This study aims to present a comprehensive decision-making, evaluation, and improvement plan for enhancing the accessibility of forested areas through road networks. Decision making systems (DMS) for road planning combine the need for accessibility improvement for prevention and suppression of forest fires (Ioannou et al., 2011 ; Gao et al., 2020 ; Tsiotas et al., 2023), as long as for regional and mountain areas development (Bournaris et al., 2021; Moulogianni and Bournaris, 2021). Recognising that firefighting operations involve ground crews that initiate suppression from the nearest points of forest roads, three evaluation criteria were applied. The first criterion employs travel time, the second involves slope-adjusted distance considering terrain incline, and the third considers horizontal distance while accounting for whether each road side is uphill or downhill. These criteria were utilised due to their relevance in assessing the suitability of forest roads for firefighting operations.

The method for assessing the accessibility of a forested area using the time is based on calculating the travel time required for a person to walk from the nearest road to a specific point within the forest. This approach was initially proposed by Hippoliti (1976) to estimate access times and thereby evaluate the accessibility of forested areas for forest workers at their job sites. Similar approaches have been employed (Laschi et al., 2016; Picchio et al., 2018; Grigolato et al., 2013) with the aim of optimising forest management, forestry operations, and timber production. The main advantage of using travel time assessment as an accessibility criterion lies in its applicability to mountainous regions, as it takes into account the terrain slope and variations. In this study, the application of the criterion is oriented towards the time needed for a section of firefighters to approach a specific point within the forest for firefighting purposes, starting from the nearest point on the road where the firefighting vehicle is assumed to be stationed.

The method for assessing the accessibility of a forested area using the fire distance criterion is based on calculating the distance of a point within the forest area from the nearest road. The primary characteristic of this method is its calculation of the distance from the nearest road at a specific point within the forest, taking into account topographic conditions, primarily the terrain slope. Similar applications of the road distance criterion for accessibility assessment were conducted by Laschi et al. (2016) and Picchio et al. (2018), who focused on estimating the slope-adjusted distance from the road network to determine the possibilities for transporting harvested wood using animal traction or machinery and the maximum cable yarding distance. Zhang et al. (2020) developed a similar criterion to calculate the maximum possible fire suppression distance, considering only the horizontal distance and not the slope due to terrain inclination. The method, as developed in this study, incorporates both slope-adjusted distance and determines the distances for deploying water delivery hoses and transporting firefighting equipment.

A quick approach to assessing the accessibility of forested areas through terrestrial forces can be realised through proximity analysis and estimation of horizontal distance from the forest road network. Several examples of this accessibility assessment have been developed in other studies (Baath et al., 2002; Lopez-Rodrigues et al., 2009), considering different distances based on the type of machinery and techniques used. The method involves creating buffer zones that represent the horizontal distance from the edge of the road within the area, accounting for the type of soil and whether it is uphill or downhill. Using the estimation of horizontal distance, the coverage area with direct fire suppression capability from the ‘water cannon’ of firefighting vehicles can be calculated, along with the distances reachable by water from the nozzle of firefighting hoses.

Following the completion of accessibility assessment by ground forces, the next objective of the research is to present a methodology for road construction and overall accessibility improvement within forest areas through the road network. This enhances forest management sustainability (Raptis et al., 2021). The goal was to ensure that the new roads pass through both inaccessible sections of the forest area and those with the highest fire hazard. The new roads are used for fire suppression and should not cause natural disturbance (Kolkos et al., 2023) Hence, a fire hazard sensitivity analysis was employed to determine the most hazardous areas in terms of fire occurrence. Various methods have been proposed for creating fire occurrence hazard maps (Sari, 2021; Iban and Sekertekin, 2022; Al-Fugara et al., 2021)

The accurate selection of factors influencing the likelihood of occurrence and propagation of a forest fire constitutes the most crucial aspect underlying the production of fire susceptibility maps (Petrakis et al., 2005). These factors can be categorised into two main groups:

a natural factors

b anthropogenic factors (Sakellariou et al., 2019; Arca et al., 2020).

In this research five factors were selected:

a the terrain slope

b the aspect

c the fuel type

d the proximity to the road network

e the proximity to settlements.

The slope of the terrain significantly influences the susceptibility of occurrence and propagation of a forest fire. The primary aspects it affects are

a the rate of its spread

b it is detection

c it is control

d it is intensity

e it is behaviour (Butler et al., 2007; MacKay and Jan, 1984; Suryabhagavan et al., 2016).

The terrain aspect significantly impacts the amount of solar radiation received, thereby influencing the rates of vegetation desiccation and the moisture content of the combustible material. South-facing slopes typically receive more direct sunlight, resulting in warmer and drier conditions. This aspect can lead to reduced fuel moisture, rendering vegetation more susceptible to ignition and facilitating the rapid spread of fire (Flannigan et al., 2000). Fuel composition and vegetation type are critical factors influencing forest fires, acting as catalysts that determine the fire’s behaviour and intensity. Fuel types refer to the various organic materials present within a forest, capable of serving as potential ignition sources. These materials can range from fine fuels, such as grasses and dead leaves, to coarse fuels, including fallen logs and branches. The type and arrangement of fuel play a pivotal role in fire ignition (Mitsopoulos et al., 2020). The distance from the road network within an area, and consequently, the passage and presence of human activities near forested environments, constitute critical factors significantly contributing to the occurrence of forest fires. A substantial number of fire ignition points are located in direct proximity to roads, and these fires can be initiated either accidentally due to irresponsible human activities or intentionally (Ruffault and Mouillot, 2017; Ager et al., 2014). Another crucial factor that increases the likelihood of fire occurrence is the proximity to settlements or built environments, as well as to recreational or tourist facilities within the forested area. Approaching forests from inhabited areas and human activities can amplify fire risks, favouring potential ignition and the rapid spread of fires (Syphard et al., 2008; Mell et al., 2010).

These five selected factors for producing fire hazard sensitivity maps contribute with varying degrees of significance, each one playing a distinct role. To estimate the weight coefficients, various methods have been proposed by different researchers. In this study, the analytical hierarchy process (AHP) method was applied (Nikhil et al., 2021; Dolui, 2023; Ljubomir et al., 2019). The AHP is a sophisticated decision-making technique that enables the evaluation and comparison of multiple criteria with the goal of selecting the optimal solution. With AHP, decisions are broken down into hierarchical levels, incorporating the opinions and preferences of involved stakeholders. The mathematical and logical approach to evaluation allows for objective conclusions to be drawn and effective preference of options, contributing to the optimisation of various decisions, from business to environmental contexts.

2 Materials and methodology

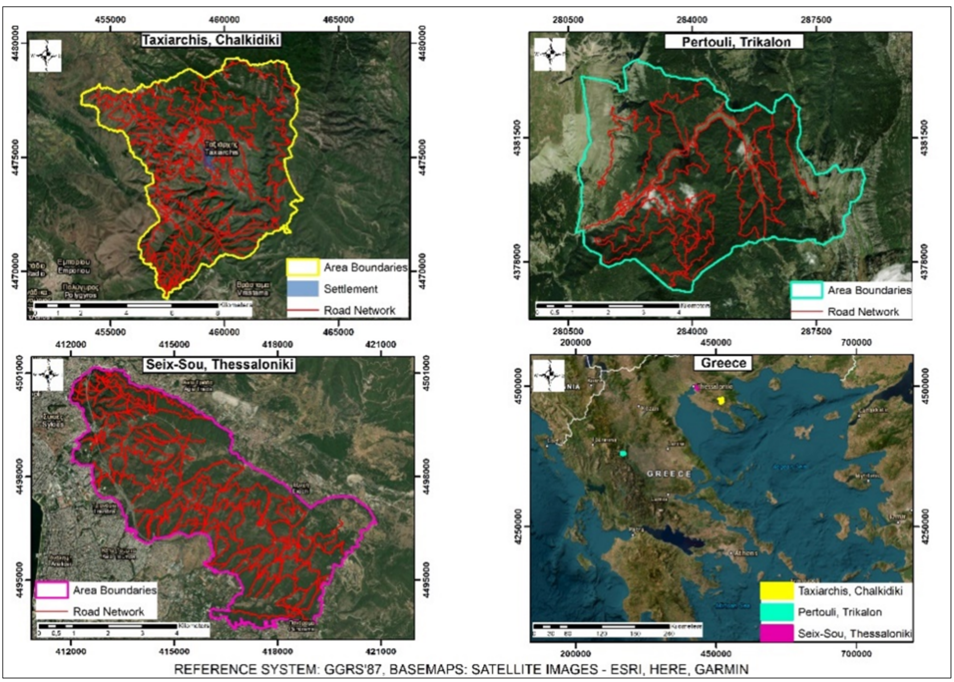
2.1 Research areas

Three areas were selected for the implementation of the present research. The forest complex of Pertouli (Trikala, Greece) which is in high altitude with dominant coniferous vegetation, the forest complex of Taxiarchis (Chalkidiki, Greece) which is in medium altitude with mixed vegetation, and the forest area of Seix-Sou (Thessaloniki, Greece) which is a peri-urban forest. The selection of three distinct forest areas – high altitude, medium altitude, and peri-urban – for the implementation of this research was driven by the need to comprehensively understand the multifaceted dynamics of forest ecosystems across varying environmental gradients. These areas were strategically chosen because they are characteristic representations of Mediterranean landscapes and provide quintessential examples of the diverse landscapes we aim to investigate.

The high-altitude forest serves as a crucial reference point for understanding road infrastructure challenges and fire management at elevated terrains, offering insights into the unique accessibility dynamics and fire vulnerabilities in alpine environments. The medium-altitude forest, as a transitional landscape, enables us to analyse accessibility patterns and fire risk factors across varying altitudes, shedding light on how forest roads and fire management strategies adapt to climatic gradients. The peri-urban forest, in turn, captures the intricate interplay between road accessibility, urban sprawl, and forest fire dynamics, serving as a microcosm of the complex interface between human development and natural resource management.

In Figure 1 locations of all three research areas is identified. The forest complex of Taxiarchis, is located in the Region District of Chalkidiki, of the Region of Macedonia in Northern Greece. The size of the area is approximately 5.870,50 ha. Since 1934 the area was granted to Aristotle University of Thessaloniki, which exploits the area for education, research and implementation of contemporary forest management. Both management and administration are conducted by the Aristotle University's Forest Administration and Management Fund. A variety of research programs which have implemented by Faculty of Forestry and Natural Environmental Studies of A.U.TH., has available a variety of scientific data regarding the topography, the road network and the forest fires factors. Within the area, the settlement of Taxiarchis is located, which according to Greek Statistics Agency has 1,070 residents, and in addition, tourist accommodations and the university's facilities. Around half of the area belongs to the Natura 2000 sites (GR127001 and GR1270012).

Figure 1 Location map of the research areas (see online version for colours)



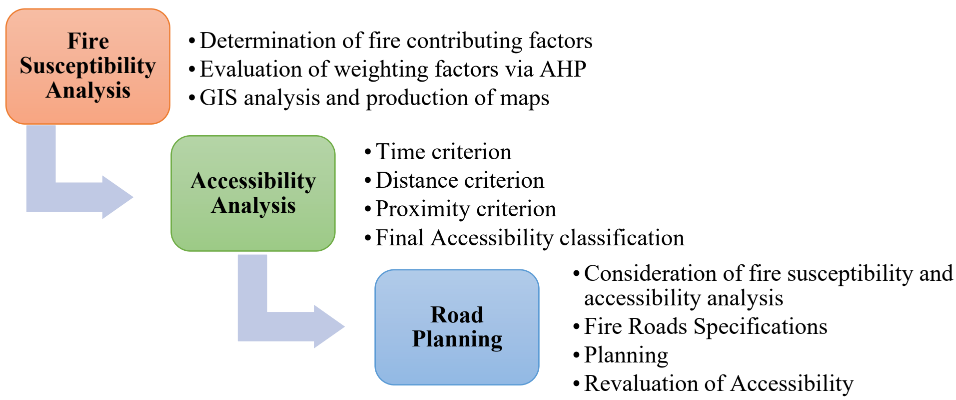
The second area of the forest complex of Pertouli, is located in Region of Thessaly in Central Greece and it covers an area of 3.289.1 ha. The Aristotle University of Thessaloniki also owns and manages the area, where student internships and research programs are taking place. The average altitude of the area is approximately around 2.000 m and dominant forest species are coniferous and particularly the *Abies borisii regis*. Within the area are the establishments of the University and the Greek Forest Agency. The only settlement of Pertouli, has around 50 permanent residents. The third research area is the Seix-Sou complex in Thessaloniki, Greece. The size of the area is 3.029.6 ha It is a typical peri-urban forest area with main vegetation species *Pinus brutia* and *Cupressus semperviern*s, and it stands as a compelling example of the delicate interface between urban expansion and natural ecosystems. Nestled on the outskirts of Thessaloniki, this forest epitomises the intricate balance between human activity and environmental preservation. Its proximity to the city makes it a vital recreational hub for residents, offering a sanctuary for outdoor activities and respite from urban life.

However, the forest also faces the pressures of urbanisation, as encroaching development places its ecological integrity at risk.

2.2 Methods

The methodology employed in this research encompasses a comprehensive approach to addressing fire susceptibility and accessibility challenges within the context of forest management and fire prevention. The first step involves conducting a fire susceptibility analysis. Through the integration of geospatial data, including topography, vegetation, and human infrastructures, fire risk maps were produced by using the AHP and GIS analysis. The fire susceptibility analysis aims to delineate areas prone to higher fire risks. The identification of such areas serves as a foundation for proactive fire management strategies.

Figure 2 Structure of the methodology (see online version for colours)



In tandem with the fire susceptibility assessment, an accessibility analysis via the road network is executed to illuminate inaccessible zones for conducting firefighting operations. Three main criteria were taken into account in order to determine the accessibility via the road network. The first was the time criterion which demonstrates the time needed for the fire foot brigades in order to move to a point in the area from the nearest point of the forest road network, where the fire engines are assumed to be parked. The second was the distance criterion which shows the slope distance of a point in the area, from the nearest point of the road network, and thereby calculates the maximum firefighting distance from the road network. The third was the proximity criterion which calculates the horizontal (buffer) distance from the road network, taking into account the uphill/downhill side of the roads. Through this the direct distance for fire fighting with watercannons is calculated. These three criteria are combined and the inaccessible areas are being estimated.

Building upon these insights, the research proceeds to combine the outcomes of both the fire susceptibility and accessibility analyses. This synthesis results in the identification of overlapping high fire risk areas and inaccessible zones providing the critical zones which need access improvement. Taking into account these critical zones, road planning was executed, based on the specifications of the forest roads, and the accessibility criteria where revaluated with the new improved road network.

2.3 Fire susceptibility analysis

The spatial analysis of the selected factors (slope, aspect, fuel type, distance from roads, distance from settlements) influencing fire ignition probability, aiming to produce fire risk susceptibility maps, was conducted within a GIS environment utilising raster modelling techniques. In order to establish the correlation among these factors, a unified classification into value ranges was necessary, with regard to their impact on fire occurrence hazard. Classification into ordered ranges on a scale from 1 to 10 was chosen, representing fire occurrence hazard levels as follows: 1 as very low, 2 as low-moderate, 3 as low, 4 as moderate-low, 5 as moderate, 6 as moderate-high, 7 as high, 8 as moderately high, 9 as very high, and 10 as extremely high.

Table 1 Rating of each factor contributing to the fire susceptibility analysis

Fire susceptibility rate	*Slope*	*Aspect*	*Fuel type*	*Proximity to roads*	*Proximity to settlements*
1 – Low risk		Flat	Artificial lands	500 m	
2	0°–3°	North			4.000 m
3	3°–5°	Northeast	Agricultural lands	400 m	
4		Northwest			
5	5°–10°	East	Forest areas: tree density 0–10%	300 m	3.000 m
6		Southeast			
7	10°–15°	West	Forest areas: tree density 10–40%	200 m	2.000 m
8		Southwest			1.000 m
9	15°–35°		Forest areas: tree density 40–100%	100 m	500 m
10 – max risk	> 35°	South			200 m

Utilising the digital elevation model (DEM) of the research areas and the GIS tools, the slope and the aspect map was produced. The values of the raster datasets were reclassified based on the ratings of Table 1. The classification of the slope was based on (Jaiswal et al., 2002), and of the aspect on (Sharma et al., 2012), while the classification of the remaining factors is original. In order to assess the fuel type factor, land use data (land cover type) and vegetation density (tree cover density) from the Corine 2018 program were utilised. Regarding the proximity to the road network, after executing the Buffer tool to create zones, the erase tool was applied for zone differentiation. Subsequently, the generated polygons were merged, and using the Polygon to Raster and reclassify tools, a raster model was created. This model was based on the values from Table 1, with a cell size similar to that of the other raster models. This was done to enable the comprehensive analysis of all factors.

2.4 Implementation of AHP method

The assessment of the weighting coefficients of the factors contributing to fire occurrence was conducted using the AHP method. This method is based on the quantification of managerial decisions based on the relative importance of multiple conflicting criteria taken into consideration (Belhaldi et al., 2017; Kumar and Garg, 2017). The application of the AHP method can be divided into four main stages:

a problem identification and model determination

b criteria evaluation and pairwise comparison matrix creation

c ranking

d synthesis.

In the initial stage, the problem is clearly defined and the primary objective is determined. The second stage involves pairwise comparison of criteria, sub-criteria, and alternatives. The subsequent significant step in implementing the AHP method is consistency checking. This step is crucial as human judgment can introduce inconsistencies.

Table 2 Criteria comparison scale when applying the analytical hierarchy process (AHP) method (Saaty, 2001)

Degree of importance	*Description*	
1	Equal importance	Both factors contribute equally to the goal
3	Moderate importance	The first criterion is slightly more important than the second
5	Strong importance	The first criterion is more important than the second
7	Very strong importance	The first criterion is much more important than the second
9	Maximised importance	The first criterion in relation to the second, has the strongest specification and preference
2, 4, 6, 8	Intermediate values	When a compromise between the above values is necessary

Equation (1) factor pairwise comparison log when performing the AHP

$$A = \begin{bmatrix} a_{11} & a_{12} \ldots\ldots\ldots\ldots & a_{1n} \\ a_{21} & a_{22} \ldots\ldots\ldots\ldots & a_{2n} \\ \ldots & \ldots\ldots\ldots\ldots\ldots & \ldots \\ \ldots & \ldots\ldots\ldots\ldots\ldots & \ldots \\ a_{n1} & a_{n2} \ldots\ldots\ldots\ldots & a_{nn} \end{bmatrix}$$

While AHP is inherently reliable, result accuracy depends on the consistency of pairwise comparisons of criteria and sub-criteria. For this reason, the CR is calculated. CR evaluates the consistency of one-by-one comparisons between criteria necessary for determining this consistency. A CR value below 0.10 allows the continuation of AHP. Any CR value exceeding 0.10 indicates an insufficiently consistent comparison matrix (Chen et al., 2010; Saaty, 2001). If this occurs, it's necessary to review and modify the comparisons to reduce inconsistency to less than 0.10. The value of the RI coefficient in the above equation depends on the number of compared factors and is derived from the method's literature as displayed on Table 3.

Equation (2) calculation of CR in the execution of AHP

$$CR = \frac{CI}{RI}, CI = \frac{\lambda max - n}{n - 1}$$

where *CR* stands for consistency ratio, *RI* refers to random index, *CI* represents consistency index, *λmax* denotes the average consistency matrix value, and *n* signifies the number of criteria being compared.

Table 3 Random index (RI) values based on the number of criteria considered in the application of AHP (Saaty, 1980)

Number of AHP criteria (n)	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI (random index)	0.00	0.00	0.58	0.90	1.12	1.24	1,32	1.41	1.45	1.49

2.5 Creation of fire susceptibility maps

The creation of fire ignition susceptibility maps is based on generating a unified raster model for each of the research areas, where the value of each cell represents the degree of susceptibility at that specific point. The estimation of the fire risk level is determined using the following equation. The results of the AHP method were used as the weightings factors. The analysis was implemented through the map algebra packages of GIS.

Equation (3) calculation of fire susceptibility through map algebra

$$FRL = s * Sl + a * As + f * Ft + r * Rd + h * SRd$$

where *FRL*: fire risk level – degree of fire susceptibility/*s, a, f, r, h*: weighting factors for each respective factor from the implementation of the AHP method, with *s* representing slope factor, *a* for aspect factor, *f* for fuel type factor, *r* for road proximity factor, and *h* for human proximity factor/*Sl*: slope – degree of soil slope sensitivity/*As*: aspect – degree of slope aspect sensitivity/*Ft*: fuel type – degree of fuel type sensitivity/*Rd*: road PROXIMITY sensitivity/*SRd* – settlement distance – degree of sensitivity to proximity to settlements.

3 Accessibility analysis

3.1 Time criterion

Regarding the calculation of the time criterion, initially, a slope map is generated for each of the research areas based on the digital terrain model (DTM). The slope map reflects the degree of slope in each cell as a percentage (p%). Subsequently, the calculation of differential levelling (d) is performed using the equation (4). Applying this, the resulting digital model represents distances for crossing each cell. The crossing time is calculated using equation (5). The climbing speed between two different altitude points by a pedestrian is considered to be 400 m/h (Laschi et al., 2016), equivalent to 0.111 m/sec. The next step involves constructing a raster model that includes the presence or absence of a road in each cell, using a value of 0 for absence and 1 for presence. Using vector line models of roads, road occupation zones (buffers) are created based on road categories. The production of the final map reflecting the travel time to each pixel within the area is accomplished using the cost distance tool. The cost distance tool calculates the least cumulative cost of movement from each cell to a set of source cells within a given raster dataset, considering the cost values associated with passing through different cells. According to the capabilities of the Greek firefighting services, areas with access times ranging from 0 to 10 minutes are considered accessible, areas with access times ranging from 10 to 30 minutes are considered partially accessible, while areas with access times exceeding 30 minutes are considered inaccessible.

Equation (4) Calculation of differential levelling for the implementation of time criterion

$$d = \frac{p_{\%} * d_0}{100}$$

where

d represents the value of differential levelling in metres (m)

$p\%$ is the percentage value of slope (%)

d_0 is the horizontal distance in metres (m) of each cell within the raster model.

Equation (5) Calculation of travel time for each cell within the raster model, during the implementation of the time criterion

$$ct = \frac{d}{t_u}$$

where

ct represents the crossing time in seconds

d is the value of differential levelling in metres (m)

t_u is the travel speed in metres per second (m/s) for crossing the cell.

3.2 Distance criterion

The accessibility assessment method of a forested area using the fire response distance criterion is based on calculating the distance from a point within the forest area to the nearest road. The DTM of the respective research area was adapted so that all cells of the digital raster model have the value of horizontal distance for passing through each cell. Subsequently, using the slope tool in GIS, the raster model of slopes for the area is generated. The crossing distance of each cell (D-crossing distance), as a function of slope p, is computed using map Algebra, in accordance with the following equation.

Equation (6) calculation of crossing distance for each cell of the digital model (raster), in the implementation of the distance criterion of accessibility

$$D = \frac{d_0}{\cos(p)}$$

where

D the crossing distance from each cell of the raster model as a function of slope in metres

d_0 the horizontal crossing distance from each cell of the raster model in metres

p the slope of the terrain in radians.

3.3 Proximity criterion

The analysis of accessibility through the proximity criterion, namely the horizontal distance from the road network, was conducted using GIS. This was accomplished by utilising the DEM of the respective research area and the road network of the regions in vector polyline format. An essential parameter considered during the application of the proximity criterion is the type of terrain structure, i.e., whether the slope on either side of the road constitutes an uphill or a downhill. The terrain structure was calculated by averaging the points difference between the road and the rest of the area. When the difference was positive then the area was uphill, while when it was negative it was downhill.

Table 4 Classes for total evaluation of the accessibility through the road network

Accessibility	*Time criterion*	*Distance criterion*	*Proximity criterion**
1 – Excellent	<= 10min	<= 50m	Zone U: 30m–F: 40m–D: 50m
2 – Good	10–30 min	50–100 m	Ζώνη U: 60m–F: 80m–D: 100m
3 – Moderate	10–30 min	100–200 m	Ζώνη U: 60m–F: 80m–D: 100m
4 – Difficult	> 30 min	200–400 m	Ζώνη U: 100m–F: 200m–D: 300m
5 – Inaccessible	> 30 min	> 400 m	Out of zone

Notes: *: The zone of proximity criterion, symbolised as follows: U for uphill sides of the roads, F for flat terrain, and D for downhill sides of the roads.

3.4 Total evaluation of accessibility

After the calculation of the all three accessibility criteria, a final assessment took place. According to the values of Table 4, the accessibility of the research areas was defined into 5 classes. The classes were defined according to the capabilities of carrying out wildfire suppression operations of the Greek fire service.

3.5 Road planning

The design of new roads aimed at improving the road network and consequently enhancing fire prevention infrastructure took into account the analysis of fire sensitivity and accessibility of the areas. The goal was to identify new branches of forest roads that would traverse regions with high fire risk and low accessibility. Utilising the intersect tool of the GIS software, the inaccessible areas from the total evaluation of the accessibility and the areas with fire risk value greater than 80, according to the fire susceptibility analysis were determined as the high-risk road planning zones. The planning of the new roads was made in CAD software by using:

a the area boundaries

b the DEM and the contours

c the high risk road planning polygons

d the existed road network

e the hydrology network for the selection of the technical infrastructures of the new roads

f maximum culvert length is 4 m and width is 2 m, shared in cuts and fills

g the land use polygons based on the Corine 2018 dataset, which represent artificial or agricultural areas, and thus potentially involve property ownership issues and finally

h aerial photographs from the Greek cadastral agency.

The specifications for the new roads planning were:

1 Minimum curvature radius R_{min} = 20 m

2 pavement width of 4 m

3 design speed is 15 km/h

4 maximum longitudinal gradient is 12% and minimum longitudinal gradient is 2% (to ensure proper water runoff)

5 construction of drainage ditches

6 construction of culverts when crossing streams

7 preferably earthworks (excavations – embankments) are done on a section-by-section basis; if not feasible, then on all sections of the area

8 all road branches have starting and ending points connected to the existing road network (this aspect was prioritised to prevent entrapment in case of firefighting operations)

9 new roads are planned as much as possible within the development access polygons

10 widening areas are implemented every 500 m along the road length to allow vehicle turning and finally

11 road design avoids artificial surfaces polygons, settlement boundaries, agricultural areas, and boundaries recognised as properties based on orthophotographs.

4 Results

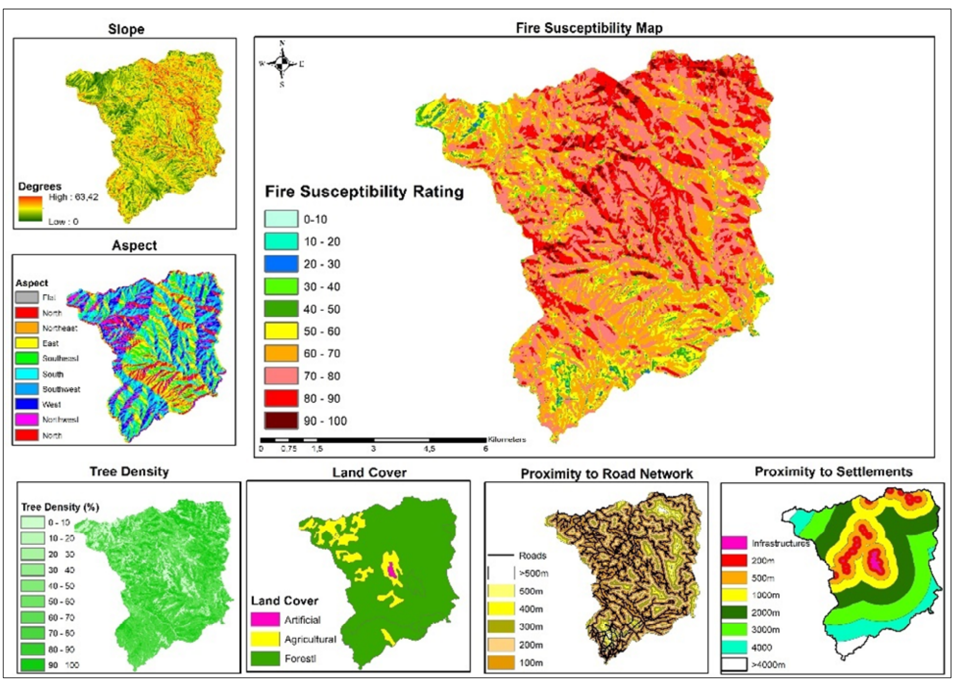
4.1 Fire susceptibility maps

The first stage of applying the AHP method for assessing the weighting coefficients of the 5 selected factors contributing to potential fire occurrence involved pairwise comparisons of the criteria based on the matrix presented in Table 5. Subsequently, the integer part of the factor comparison was computed, and the column sums were calculated. Following this, the normalised matrix was constructed by dividing each value of the comparison matrix by the sum of the corresponding column elements. Next, the methodology for calculating the CR – consistency ratio was applied to ensure consistency. The results were aggregated to yield the weighted sum of values by row. The weighted sum by row was multiplied by the respective weighting coefficient, resulting in the consistency value λ for each criterion.

Table 5 Pairwise matrix for the implementation of the AHP method

Criteria	*Slope*	*Aspect*	*Fuel type*	*Distance from roads*	*Distance from Settlements*
Slope	1	2	6	2	2
Aspect	1/2	1	5	2	2
Fuel type	1/6	1/5	1	1/4	1/4
Distance from roads	1/2	1/2	4	1	1
Distance from settlements	1/2	1/2	4	1	1

Figure 3 Spatial data analysis and creation of fire susceptibility map for the research area of Taxiarchis (see online version for colours)

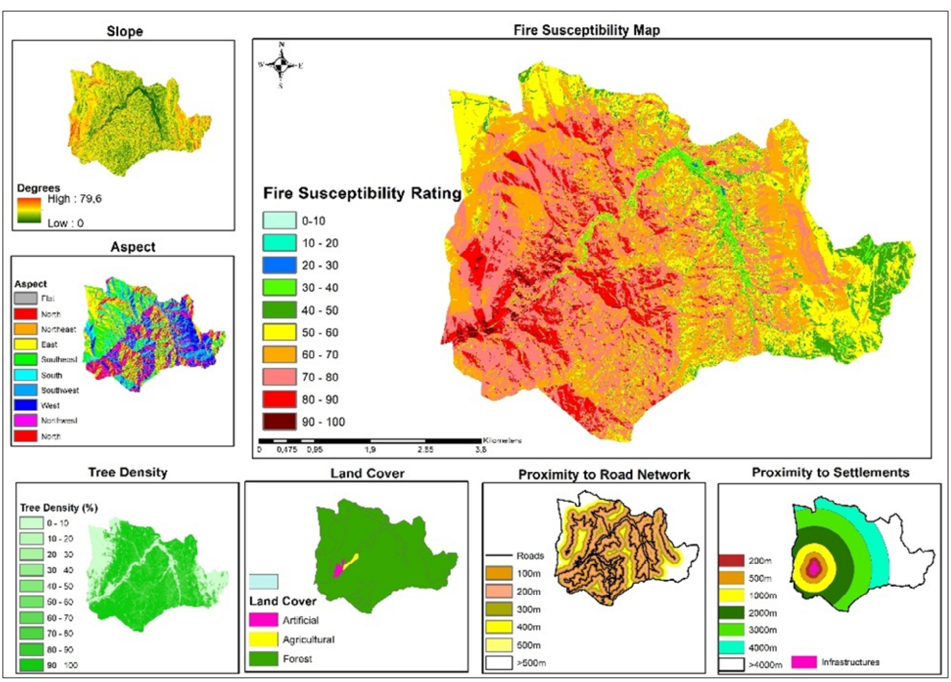


The consistency index CI for a total of 5 criteria was obtained using equation (2) was equal to 0.01966. The CR was computed using equation (2) and the random index RI for 5 criteria, based on the values from Table 3: CR = 0.01966/1.12 → CR = 0.01756 < 0.10. Given that the CR value is less than 0.10, the consistency check of the AHP method for pairwise comparisons is considered acceptable. The final weighting coefficient values obtained from the AHP method were multiplied by 10 and rounded to the first decimal place, in order to ensure their sum equals 10. By doing so, when applying equation (3), the degree of hazard for each cell in the final hazard map could be assigned integer values ranging from 1 to 100. The final weighting coefficients which resulted from the AHP method, for the implementation of equation (3) in map algebra, were: slope = 3.50/aspect = 2.60/fuel type = 0.50/proximity to roads = 1.70/proximity to settlements = 1.70.

Table 6 Area coverage according to fire susceptibility risk level for the research areas

Fire risk level	*Percent of total area*		
	Taxiarchis	*Pertouli*	*Seix Sou*
10–20	0.03%	0.02%	0.01%
20–30	0.46%	0.19%	0.22%
30–40	1.56%	2.22%	1.27%
40–50	3.18%	6.57%	3.32%
50–60	11.62%	19.86%	9.41%
60–70	28.49%	30.91%	23.67%
70–80	34.39%	29.15%	37.99%
80–90	18.47%	10.32%	22.52%
90–100	1.81%	0.77%	1.58%

Figure 4 Spatial data analysis and creation of fire susceptibility map for the research area of Pertouli (see online version for colours)



After the implementation of the AHP and the calculation of weighting factors the Map Algebra was executed according to the equation (3). The fire risk values for each research area are presented in the following table. In the research area of Taxiarchis, the total size of the area with fire risk level greater than 80 covers 54.67% of the total area. The same value in the research area of Pertouli is 40.24% and in the research area of Seix Sou is 62.01%. These areas with fire risk values greater than 80, were intersected with the accessibility results for the calculation of the road planning zones.

Table 7 Area coverage based on the time criterion of accessibility of each research area

Time zone	*Percent of total area*		
	Taxiarchis	*Pertouli*	*Seix Sou*
0–2 min	12.69%	3.71%	6.25%
2–4 min	8.27%	2.67%	3.22%
4–6 min	7.23%	2.25%	2.93%
6–8 min	6.28%	1.97%	2.68%
8–10 min	5.52%	1.69%	2.47%
10–15 min	11.34%	3.83%	5.66%
15–20 min	8.91%	3.40%	4.89%
20–25 min	7.35%	3.20%	4.14%
25–30 min	5.83%	2.99%	3.48%
> 30 min	26.57%	74.29%	64.28%

5 Accessibility analysis

5.1 Time criterion

In Table 5, the total area for each time zone which created with the time criterion of accessibility is presented. The time criterion excludes the areas with steep slopes greater than 45^{o} or 100%. Extinguishing forest fires is critical within the least response time. Thus, the areas within 10 min of walking time from the road network are considered the most accessible. These areas cover the 39.99% of the area of Taxiarchis, the 12.29% of the area of Pertouli and the 17.55% of the area of Seix Sou. After the 10 min zone, the ground firefighting forces it is difficult to attempt because the behaviour of the fire can change unexpectedly and there will be a safety hazard. The areas which the walking time in order to reach them is greater than 30 min, are considered inaccessible.

5.2 Distance criterion

According to Greek forest fire service, the fire hoses equipment is limited to 50 m length. This makes only the areas of the first zone of 50 m slope distance as accessible. However, apart from the conventional suppression of forest fires using water, there are other methods such as vegetation backfires and the creation of firebreaks. In such cases, heavy tracked machinery is employed. In each of these scenarios, crossing the zone of the 400-metre inclined distance is deemed impractical for implementing firefighting operations.

Figure 5 Calculation of the time criterion of the accessibility analysis in all three research areas (see online version for colours)

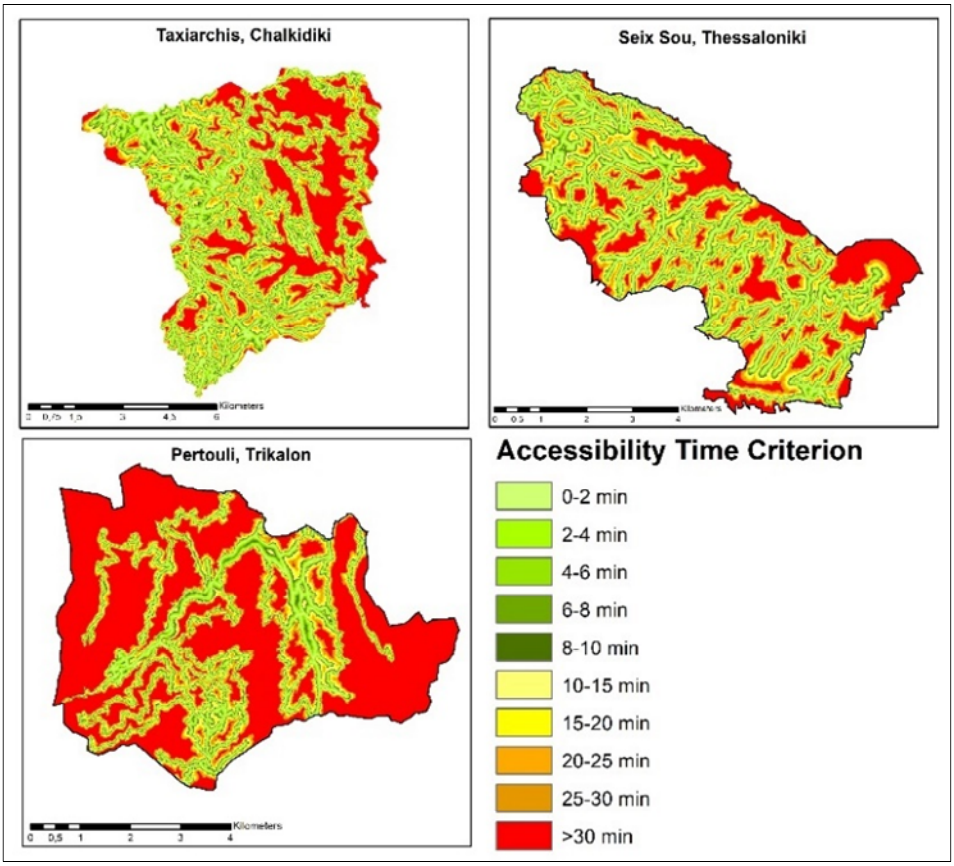
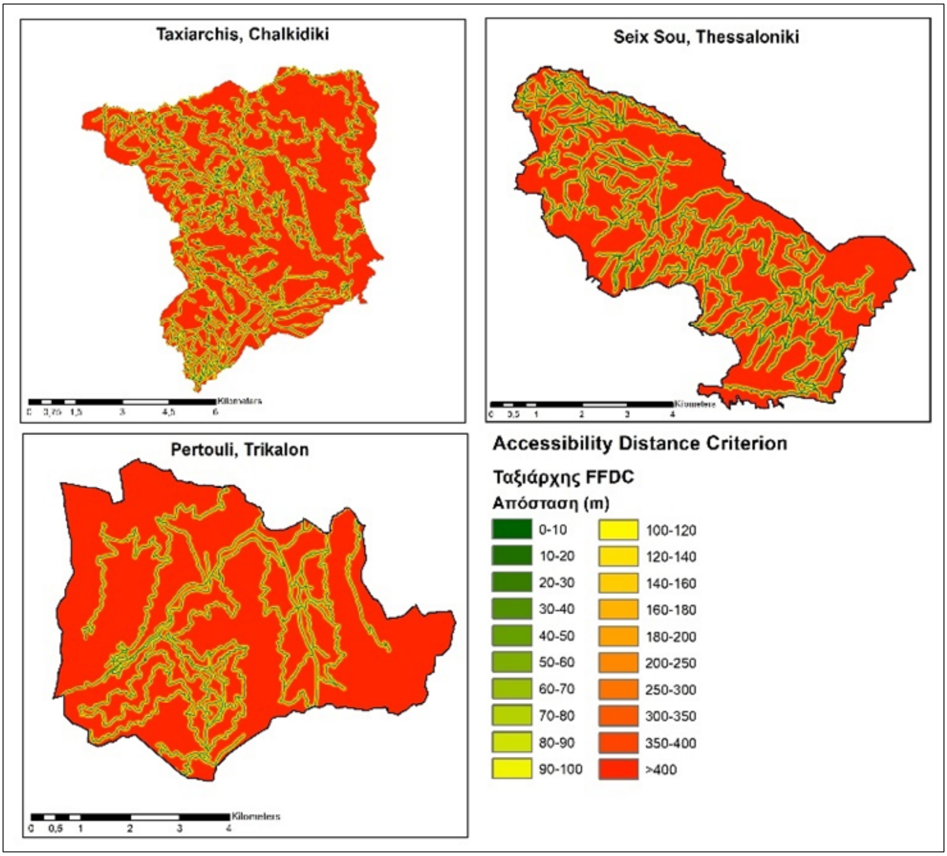


Table 8 Area coverage based on the distance criterion of accessibility of each research area

Distance zone	*Percent of total area*		
	Taxiarchis	*Pertouli*	*Seix Sou*
0–50 m	9.56%	3.70%	5.72%
50–100 m	6.75%	2.59%	2.91%
100–200 m	12.73%	4.75%	5.17%
200–300 m	10.94%	4.41%	4.73%
300–400m	9.52%	4.03%	4.21%
> 400 m	50.50%	80.53%	77.28%

Figure 6 Calculation of the distance criterion of the accessibility analysis in all three research areas (see online version for colours)



5.3 Proximity criterion

The accessibility zones created with the proximity criterion take into account the terrain structure. The zones were created with different values according to the uphill or downhill side of the road. The results are showed in Figure 7. The first zone, with the best accessibility has 15 m distance in the uphill side, 20 m in the flat areas and 25 m in downhill areas. Within this zone the ground firefighting forces can you the watercannons of the vehicles. The first zone covers the 16.27% of the area of Taxiarchis, the 11.21% of the area of Pertouli and the 21.13% of the area of Seix Sou. The second zone, where the water canons of the fire fighting vehicles can operate under circumstances, has 30 m distance in the uphill side of the roads, 40 m on the flat areas and 5 0m on the uphill side of the roads. Its coverage, which includes the first zone, is 30.96% in the area of Taxiarchis, 20.87% in the area of Pertouli and 36.95% in the area of Seix Sou. The third, which the operation of the vehicles watercannons is difficult, has 60 m distance in the uphill side, 80 m in the flat areas and 100 m on the downhill side of the roads. It covers (including the previous first and second zone) 55.01% of the area of Taxiarchis, 36.14% of the area of Pertouli and 60.59% of the area of Taxiarchis. The fourth and last zone which was estimated, was determined based on the fact that it is the maximum zone where the ground forest vehicles can operate. It has 100 m distance on the uphill side of the roads, 200 m on the flat areas and 300 m on the downhill side. Its coverage has the percent of the total area which pass the proximity criterion. The total area of Taxiarchis within this zone is 86.80%, of Pertouli 54.57% and of Seix Sou 84.76%.

Figure 7 Calculation of the proximity to road network criterion of the accessibility analysis in all three research areas (see online version for colours)

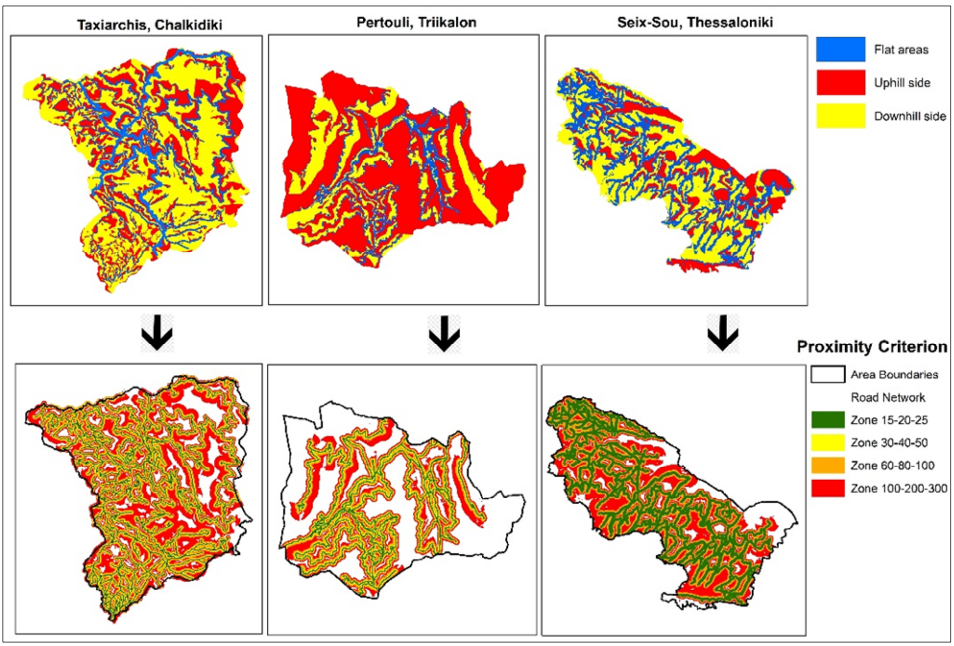
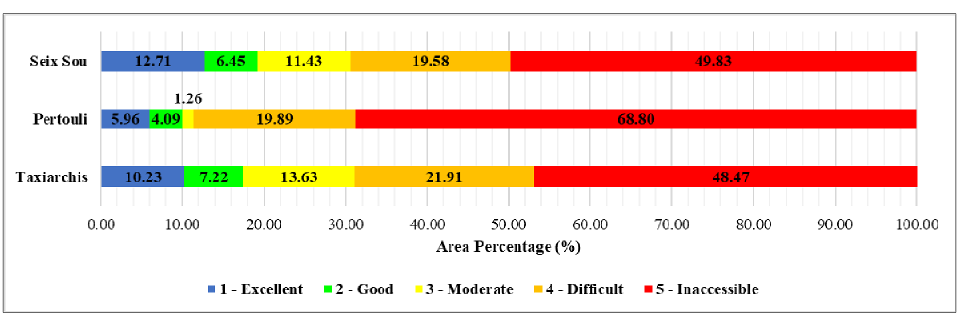


Figure 8 Total evaluation of the accessibility of the research areas (see online version for colours)



5.4 *Total evaluation of accessibility*

According to the values of Table 4, the total accessibility of the three research areas was estimated. In the research area of Taxiarchis the 10.23% is considered with excellent accessibility, the 7.22% with good accessibility, the 13.63% with moderate accessibility and the 21.91% with difficult accessibility. Thus, the total accessible areas of Taxiarchis are 53% and the inaccessible are 47% of the total area. In the research area of Pertouli the 5.96% is considered with excellent accessibility, the 4.09% with good accessibility, the 1.26% with moderate accessibility and the 19.89% with difficult accessibility. The total accessible areas of Pertouli are 31.20% and the inaccessible are 68.80% of the total area. In the research area of Seix Sou the 12.71% is considered with excellent accessibility, the 6.45% with good accessibility, the 11.43% with moderate accessibility and the 19.58% with difficult accessibility. Thus, the total accessible areas of Seix Sou are 50.17% and the inaccessible are 49.83% of the total area.

5.5 Road planning

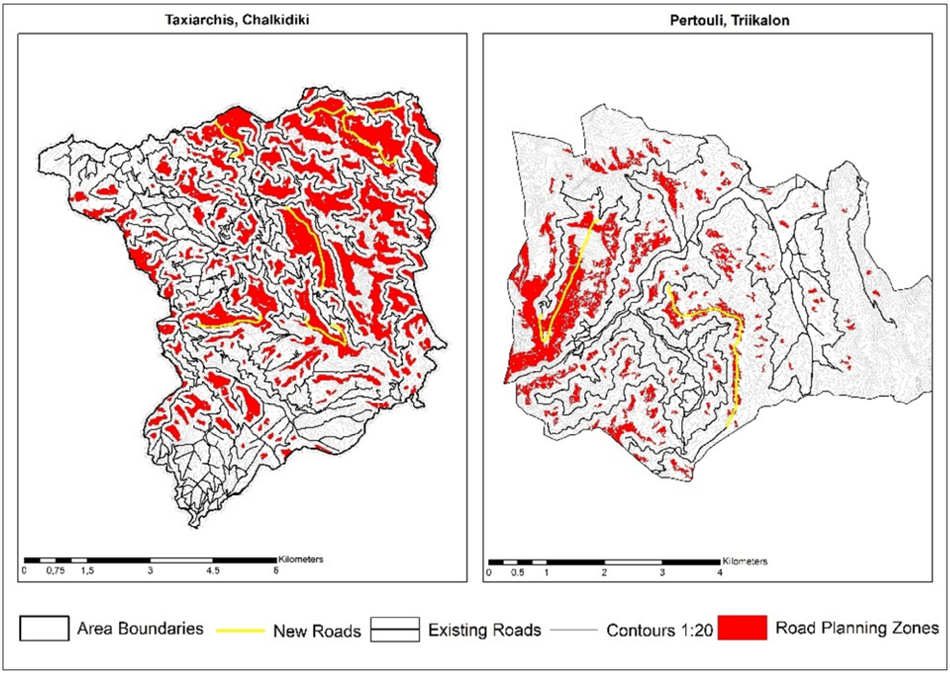
The road planning zones were estimated through the intersection of the high fire risk areas, with values between 80 and 100 according to the fire susceptibility analysis and the inaccessible areas. The sections with size less than 3.000 m^2 were not taken under consideration because of their very small size. The total size of the road plan zones of Taxiarchis was 1.148.1 ha which corresponds to 19.56% of the total area. In the area of Pertouli the road plan zones were 351.9 ha which corresponds to 10.70% of the total area. Finally, the road plan zones in the area of Seix Sou was 341.7 ha, which corresponds to 11.28% of the total area.

Having determined the road plan zones (the inaccessible and with high fire risk areas) the new roads were designed according to the specifications, which were described in the methodology. In the area of Taxiarchis seven sections of new forest roads were designed with total length of 11.461 m, while in the area of Pertouli two sections of new forest roads were designed, with total length 6.570 m. In the area of Seix Sou, due to the high road density, the small size of the road plan zones and the overall distribution of the existed road network, new roads were not designed.

5.6 Revaluation of accessibility

After the planning of the new roads for the research areas of Taxiarchis and Pertouli, the time and distance criterion of accessibility were reassessed. In the area of Taxiarchis, the area within the 10 min zone according to the time criterion covers now the 46.71% of the total area, while previous from the new roads was 39.99%, and the area within the 30min zone covers now the 81.08% while previous the implementation of the new roads was 73.42%. Regarding the distance criterion the area within the 0–50 m zone covers, with the new roads, the 11.53% and the area within the 0-400m zone covers now the 56.5% of the total area. In the area of Pertouli, the new roads have increased the area within the 10min zone to 14.23% while previous was 12.29%. The area within the 30 min zone is now 31.64% while previous covered the 25.71% of the total area. The reassessment of the distance criterion in the area of Pertouli, showed that the 4.29% is now within the 50 m zones and the area within the 0–400 m zone is now 25.72% while previous was 22.72%.

Figure 9 Results from planning new roads for the improvement of high fire risk and inaccessible areas (see online version for colours)



6 Discussion

The results of the accessibility analysis showed that the three research areas differed significantly in terms of their accessibility for firefighting operations. The research area of Taxiarchis had the highest percentage of accessible areas (53%) and the lowest percentage of inaccessible areas (47%), while the research area of Pertouli had the lowest percentage of accessible areas (11%) and the highest percentage of inaccessible areas (89%). The research area of Seix Sou had a moderate level of accessibility, with 34% of the area being accessible and 66% being inaccessible. The differences in accessibility can be attributed to various factors, such as the topography, vegetation cover, and road network of each area. For example, the research area of Pertouli is characterised by steep slopes, dense vegetation, and limited road network, which make it difficult for firefighting vehicles to access the area. On the other hand, the research area of Taxiarchis has a relatively flat terrain, sparse vegetation, and a well-developed road network, which make it easier for firefighting vehicles to access the area. The proposed road planning methodology was able to significantly improve the accessibility of the research areas for firefighting operations. The results showed that the implementation of the new forest roads increased the percentage of accessible areas in all three research areas. For example, in the research area of Pertouli, the percentage of accessible areas increased from 11% to 28%, while the percentage of inaccessible areas decreased from 89% to 72%. Similarly, in the research area of Seix Sou, the percentage of accessible areas increased from 34% to 47%, while the percentage of inaccessible areas decreased from

66% to 53%. Overall, the results of the study demonstrate the importance of evaluating and enhancing the accessibility of forest areas for firefighting operations. The proposed methodology can be used to identify the critical zones that require access improvement and design new forest roads to connect these zones to the existing road network. By improving the accessibility of forest areas, forest managers and firefighting agencies can increase the efficiency and effectiveness of their operations and reduce the risk of wildfires.

7 Conclusions

The study found that the combination of fire susceptibility analysis and accessibility analysis can provide valuable insights into the spatial distribution of fire risk and the accessibility of forest areas for firefighting operations. By identifying the critical zones that require access improvement, forest managers and firefighting agencies can prioritise their efforts and resources to maximise the effectiveness of their operations. The proposed methodology for road planning and accessibility enhancement can be customised to suit the specific needs and characteristics of different forest areas. For example, in areas with steep slopes and dense vegetation, the road network may need to be designed to follow the natural contours of the terrain and avoid areas with high fire risk. In areas with limited water resources, the road network may need to be designed to provide access to water sources and maximise the coverage of water cannons.

The results of the analysis showed that the accessibility of the three research areas varied significantly, with some areas being highly accessible and others being difficult to access. The importance of stakeholder engagement and collaboration in forest management is crucial for forest fire suppression. and collaboration in forest management and firefighting. The results of the road planning showed that the proposed methodology can significantly improve the accessibility of the forest areas for firefighting operations. By involving local communities, forest owners, and other stakeholders in the planning and decision-making process, forest managers and firefighting agencies can ensure that their efforts are aligned with the needs and priorities of the local communities and that the proposed solutions are socially and environmentally sustainable. The proposed methodology can be applied in real-world forest management and firefighting scenarios to improve the efficiency and effectiveness of firefighting operations. However, the study also highlighted some limitations and challenges of using GIS and fire susceptibility analysis, such as the need for accurate and up-to-date data, the complexity of the analysis, and the potential for errors and uncertainties. Therefore, further research is needed to address these issues and improve the reliability and applicability of the proposed methodology.

Finally, the study emphasised the need for continuous monitoring and evaluation of the effectiveness of the proposed solutions. By collecting and analysing data on the accessibility of forest areas, the spatial distribution of fire risk, and the outcomes of firefighting operations, forest managers and firefighting agencies can identify areas for improvement and adjust their strategies and tactics accordingly. This can help to ensure that the forest areas are protected from wildfires and that the firefighting operations are efficient, effective, and sustainable over the long term.

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