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Determination of fire-access zones along road networks in fire-sensitive forests

Abdullah Emin Akay[1] · Michael G. Wing[2] · Murat Zengin[3] · Osman Kose[4]

Abstract Wild forest fires are one of the greatest environmental disasters affecting forest resources. Along the coastal zone of the Mediterranean region in Turkey, forested areas are classified as first-degree, fire-sensitive areas. Every year, thousands of hectares of forests have been destroyed in Turkey. In this study, fire-access zones were determined in the Mediterranean forests of Turkey, by utilizing geographic information systems (GIS) technology. The effective reach distance of fire hoses from both sides of roads was considered in order to delineate fire-access zones. The effective reach distance can vary based on the technical capabilities and hydraulic capacity of fire trucks (minimum and maximum pressures on water pump); terrain structures (uphill, downhill and flat); and ground slope. These factors and their influences were studied in fire sensitive forest areas located in the eastern Mediterranean city of Kahramanmaraş in Turkey. First, terrain structures on both sides of the road network and ground-slope classes were determined based on GIS data layers. Then, fire access zones were delineated according to water pressure data, terrain structures, and ground-slope classes. The results indicated that 69.30 % of the forested areas were within the fire-access zones, while the rest of the forest was out of reach the fire hoses. The accessible areas were also calculated for forested areas with different fire-sensitivity degrees. The accessible areas were 69.59, 69.96, and 67.16 % for the forested areas that are sensitive to fires at the first, second, and third degrees, respectively. This finding has implications for the monitoring and management of fire threats in areas outside of the reach distance. The outside areas should receive extra attention and monitoring during the fire season so that fires are detected ahead of time and management has sufficient time to react. Besides, new roads should be considered for these areas in order to access more lands in a shorter amount of time.

Keywords Fire equipment · Fire protection areas · Forest fires · Terrain structures

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Introduction

As one of the most important natural resources in the world, forests have essential functions such as improving biodiversity, preventing air pollution, protecting soil, and preserving water (Akbulak and Özdemir 2008). In order to sustain these crucial functions, forests should be managed by considering their social, economic, environmental, and socio-cultural factors (Wilkie et al. 2003). In the last several

decades, increasing population growth and consumer demand for forest resources have increased public pressure, resulting in detrimental reactions such as illegal harvesting and forest fires. Forest fires seriously damage forest resources throughout the world especially in the Mediterranean countries (Greece, Italy, Spain, Turkey etc.) that typically have high temperatures and scant precipitation during the fire season (Demir et al. 2009; Sivrikaya et al. 2011).

About 5.5 million hectares of forest lands, along the coastline of Turkey from the eastern Mediterranean region to the Marmara region, are classified as first-degree fire sensitive areas. Almost 90 % of the forest fires in Turkey occur in this area where an average of 10,000 ha forests are destroyed annually (Akay et al. 2012). Approximately 12,000 fire fighters work during the fire season to fight forest fires (Oguz et al. 2011).

The ground teams are the most important fire-fighting resource and reach the fire areas by fire trucks to initiate fire-fighting activities. The fire trucks usually park at the nearest road-side point to the fire area and spread water and chemical foams through fire hoses. The effective-reach distance of the fire-hoses from both sides of the road are defined as fire-access zones that vary with terrain structure (downhill, uphill, flat), ground slope classes, and the technical capabilities of a fire truck. It is critical that fire-access zones can be reached by these fire-fighting teams to prevent and suppress forest fires.

In recent years, geographical information systems (GIS) data have been used to develop decision-support systems that are effectively utilized in many forestry activities (Sivrikaya et al. 2007, Yuksel et al. 2008; Akay et al. 2008; Gumusay and Sahin 2009; Wing et al. 2010). These kinds of systems have been also used in planning, managing, and decision-making stages of fire-fighting activities (Kucuk and Bilgili 2006; Durmaz et al. 2006; Sağlam et al. 2008; Demir et al. 2009; Akay et al. 2010, 2012; Sivrikaya et al. 2014; Dindaroğlu et al. 2014).

Acuna et al. (2010) developed a spatial fire and forest management planning methodology based on fire occurrence, suppression, fire protection value assessment, and spatial forest planning. Majlingova (2012) conducted a study where GIS technologies were used to assess opening up an area of a sample forest management district in Slovakia for the purpose of suppressing forest fires with the use of mobile fire apparatus.

Drosos et al. (2014a) conducted a study where an optimization model was evaluated for opening up mountainous forest areas by considering the prevention and suppression of forest fires. In order to determine the forest areas being protected by fire trucks, various fire-suppression buffer zones with a capacity radius of 150–300 m uphill and 250–500 m downhill from a location where fire trucks stand were established.

Stergiadou (2014) studied the effectiveness of road networks and water tanks located near the forest roads in prevention and suppression of forest fires. The field study was conducted in the University Forest area of Pertouli in the city of Trikala in Greece. Six main factors—such as forest road networks, infrastructures (i.e. water tanks, water ponds), climatic conditions, forest orientation, water basins, and fire hazards—were evaluated to develop a fire-protection plan. They suggested that an appropriate road network with proper signs and adequately distributed infrastructures within the forest land are very important for prevention and suppression of forest fires.

In a most recent study, Yakubu et al. (2015) synthesized various methods that were utilized for modelling forest fire risks and hazards. They reported that combination of spatial multi-criteria modelling and evaluation method was more efficient than using individual methods. They indicated that forest roads play a very important role in terms of accessibility, however, road network might increase the risk of fire since humidity drops and wind speed increases along the roadway.

In this study, GIS technology was used to determine fire access zones in forested areas by using the effective reach distance of fire hoses from both sides of the roads, considering terrain structure (uphill, downhill, and flat), ground slope, and the technical capabilities of the fire trucks.

Materials and methods

Study area

The study area covers three Forestry Enterprise Directorates (FEDs) including Kahramanmaraş, Andırın, and Göksun located in the Mediterranean city of Kahramanmaraş (x: 1309424–1443014, y: 4159659–4322312; UTM ED 50 Datum Zone 35 N) (Fig. 1). According to General Directorate of Forestry, these directorates are classified as 1st, 2nd, and 3rd degree fire-sensitive areas, respectively (Akay et al. 2012). The Kahramanmaraş region in general is vulnerable to forest fires due to high temperatures and low precipitation during the fire season. The main species in the area are Brutian Pine (*Pinus brutia* Ten.), Anatolian Black Pine (*Pinus nigra* J.F. Arnold subsp.), Sedar (*Cedrus libani*), Oak (*Quercus* spp.), and shrubs.

Generation of GIS database

A GIS database was generated through ArcGIS 10 software based on spatial information from topographic maps (1:25000), forest management maps (1:25000), a Digital Elevation Model (DEM) derived from ASTER 2010
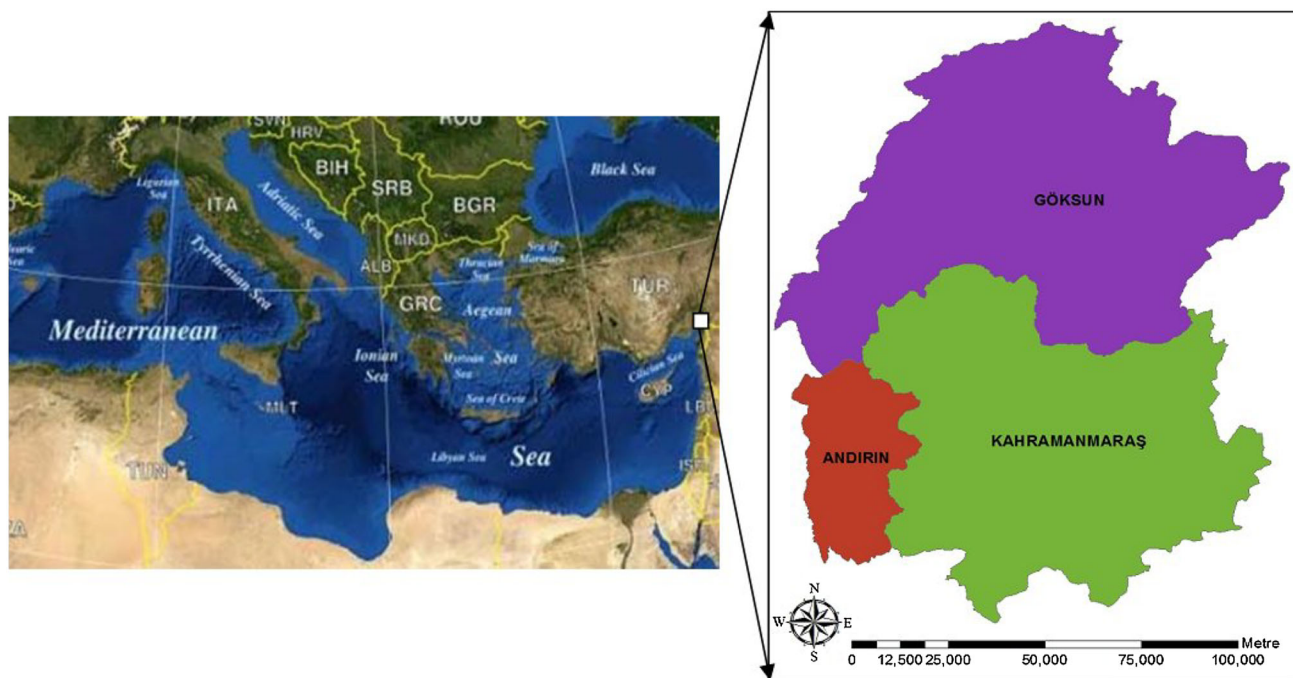
Fig. 1 The three Forestry Enterprise Directorates within the study area

satellite imagery (15 × 15 m), and a fire sensitivity map of Turkey. Using the spatial information, new GIS layers—including the maps of road network, land use, fire sensitivity, and ground slope—were generated.

Topographic maps were used to generate road-network maps. The landuse map was produced based on the current forest-management map provided by the FEDs. A data layer of forest land was then generated by reclassifying the land-use map. A fire-sensitivity map indicating fire-sensitivity degrees of the FEDs was produced, based on a fire-sensitivity map of Turkey obtained from the General Directorate of Forestry.

The fire-sensitivity level is determined based on the fire coefficient, which is computed by using the number of fire incidents and burned areas per year as follows (Yucel 1998):

$$F_c = N_c + A_c \qquad (1)$$

where F_c is fire coefficient, N_c is the coefficient for number of forest fires, and A_c is the coefficient for fire burned areas.

$$N_c = 100 x K x N_f / A_f \qquad (2)$$

$$A_c = 100 x A_b / A_f \qquad (3)$$

where N_f is the average number of fire incident per year, A_f is the forested area (ha), and A_b is the average amount of fire burned areas per year (ha).

K is estimated as 12.74 by dividing the amount of fire-burned areas by the number of fire incidents based on long-term fire data collected in Turkey. Finally, fire sensitivity

level is determined as first degree if the fire coefficient is less than 0.35. If it is 0.35–0.20 and 0.2–0.1, fire-sensitivity levels are determined the second and the third degree, respectively (Kucuk and Unal 2005).

The forest land and fire-sensitivity layers were combined within a GIS to determine the fire sensitivity of forest land in the study area. In addition, a ground-slope map was produced by using the DEM derived from the ASTER 2010 satellite imagery. In this map, ground slope was divided into four ground-slope classes; (1) low: 0–15 %; (2) medium: 15–30 %; (3) high: 30–60 % and (4) very high: >60 %.

Determination of terrain structures

Fire trucks parked at the nearest road-side point spread water and chemical foams. Terrain structure and ground slope influence the effective reach of fire hoses. These hoses can be connected in series to increase the effective length so that a fire-fighting team can reach longer distances.

Terrain structure was based on a reference surface of the whole study area, which was based on the surface elevation of the road-network layer. In the process of producing the reference surface, several datalayer manipulations had to occur. First, the road-network and DEM layers of the study area were converted into point layers by using ArcGIS 10. Second, elevation values were assigned to each point of the converted road network and DEM layers. Then, each point

of DEM layer was assigned the elevation of the nearest point on the road network layer by using the spatial join feature in ArcGIS 10. The attribute table of the reference surface data had two new fields, including the DEM elevation and elevation data representing the reference surface.

A new database representing terrain structure types was generated by subtracting the elevation values of the reference surface from the elevation values of DEM. The positive values under the terrain structure represent uphill areas, the negative values represent downhill areas, and terrain structure is defined as having no slope (flat) if the resulting value is zero. Then, these values were used to generate raster data layers for downhill, uphill, and flat areas in the study area. Finally, downhill, uphill, and flat areas within the forested areas were determined by masking out these data layers from the forest data layer.

Delineation of fire access zones

In order to map fire-access zones in the forested areas, the effective reach distances of fire hoses from both sides of the road network were determined based on technical capabilities of fire trucks, terrain structures, and ground slope. Fire-access zone widths were computed for downhill (FAZ$_d$), uphill (FAZ$_u$), and flat (FAZ$_f$) areas by using the following formulas:

$$FAZ_d = [(P_{max} - P_{min})/(\Delta P - G)] \times 10 \qquad (4)$$

$$FAZ_u = [(P_{max} - P_{min})/(\Delta P + G)] \times 10 \qquad (5)$$

$$FAZ_f = [(P_{max} - P_{min})/(\Delta P)] \times 10 \qquad (6)$$

where P_{max} is the maximum water pressure at the pump (bar), P_{min} the minimum water pressure required for ideal water discharge from the nozzle (bar), ΔP the water pressure loss for each 10 m distance from the fire truck due to friction (bar), and G is the ground slope (percent).

In Turkey, Mercedes UNIMOG model trucks are widely used in fire-fighting activities (Table 1). They are generally equipped with fire hoses that can be connected to each other up to a total length of 2,000 m. They are usually equipped with ZIEGLER model water pumps. In applications, the maximum water pressure at the pump and minimum required water pressure at the nozzle is considered as 40 and 6 bar, respectively. The water pressure loss due to the horizontal distance between location of fire truck and the end of fire hose changes depending on the diameter of fire hoses.

Taking ground slope into account, fire access zone (FAZ) widths were computed for three different ground slope classes (low, medium, and high). Since it is very dangerous and inefficient to fight forest fires on steep ground slopes, the areas with very high slope (more than

Table 1 Specifications of a sample fire truck (Mercedes UNIMOG U 2150L 4X4)

Technical features	Values
Weight (Total Weight)	12500 kg
Front Axles	5300 kg
Rear Axles	7200 kg
Dimensions (Width)	2.40 m
Length	6.80 m
Wheelbase	3.85 m
Height	3.00 m
Tires (Dimension/Number)	13.00 R 22.5/4 + 1
Engine (Power)	159 kW (214 hp)
Number of Cylinder	6
Volume of Cylinder	5958 cm^3

60 %) were not evaluated at this stage. In addition, the weight of the hose when filled with water is a limiting factor on steep slopes. In some cases, it might be necessary to use anchor points with winch systems in order to move hoses on steep grounds.

The net fire access zones (NFAZ) were computed by adding the water spread distance onto the FAZ widths. The water spread distance, which is the distance from the nozzle to the reach point of water in the field, varies by the diameter of the nozzle opening and water pressure. The water spread distance varies from 20 to 30 meters for water discharge pressure of 6 bar at nozzle openings of 0.8–1.6 cm, respectively. ArcGIS 10 software was used to perform a buffer analysis along the roadway to determine the area of NFAZ on both sides of road network.

Results

GIS data layers

The total length of the road network in the study area was 29,900 km. The largest proportion of the road network was forest roads (55.71 %), followed by gravel roads (39.07 %) and asphalt roads (5.22 %). The resulting road network generated based on the topographic maps revealed a relatively dense geometric configuration (Fig. 2).

According to the land-use map, there were 19 different land use types in the study area (Fig. 3). The largest one was high forest (453,731 ha), followed by agricultural areas (40,6103 ha), and forest soil (i.e. grasslands, plateaus, and steppes without trees) (385,842 ha) (Table 2). After combining the areas of high forest and coppice forest (47,084 ha), a new data layer indicating only the forest land area was generated. It was found that the total area of
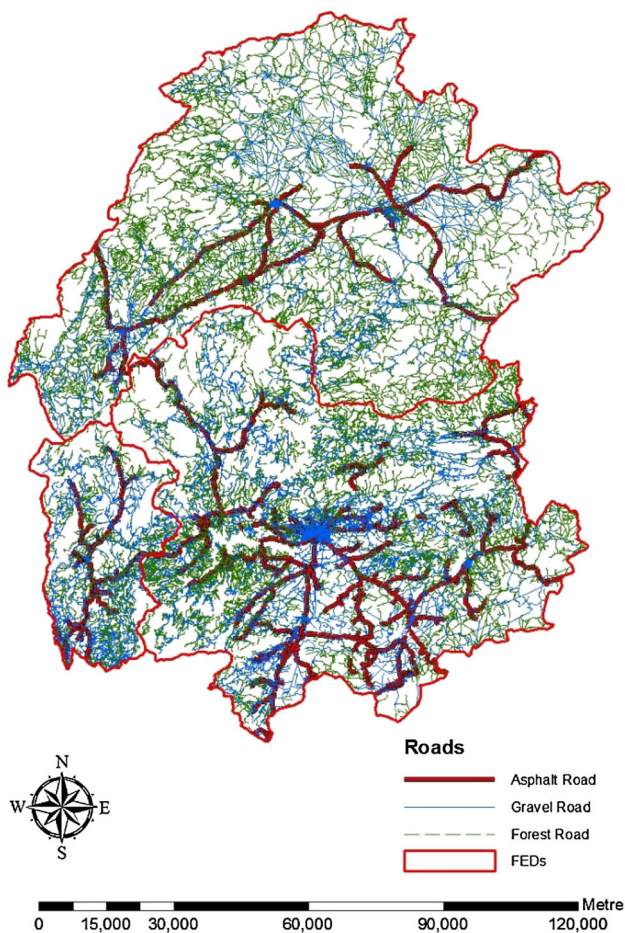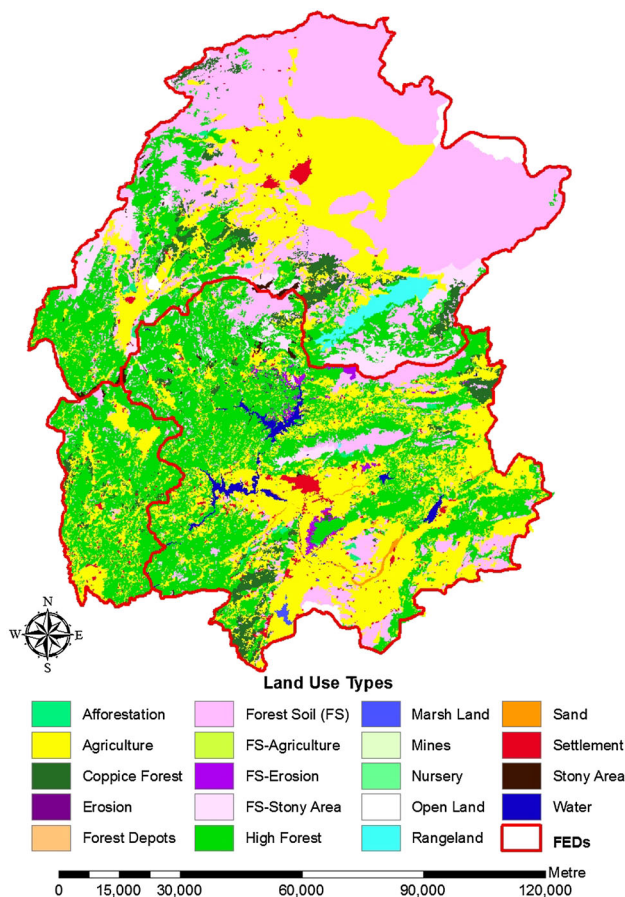
Fig. 2 Road network map in the study area

Fig. 3 Land-use types map of the study area

forest land was 500,815 ha, which was about 35.59 % of the study area.

The study area consisted of FEDs sensitive to forest fires at the first (Kahramanmaraş), second (Göksun), and third degrees (Andırın). Some 44 % of the study area was sensitive to forest fires at the first degree, while 48 % at the second degree. The rest of the area (8 %) was sensitive to forest fires at the third degree. Considering fire sensitivity of the forest land in the study area, more than half was judged to be sensitive to fire at the first (56 %), second (28 %), and the third degrees (16 %). The ground slope map of the forest land was generated based on an ASTER 2010- based DEM of the study area. Average elevation and ground slope was 1323 m and 19.74 %, respectively. Then, a new slope layer indicating four different ground-slope classes (low, medium, high, and very high) were generated (Fig. 4).

Terrain structures and fire access zones

To determine terrain structure, elevation values of the reference surface were subtracted from elevation values of the DEM. It was found that the downhill and uphill areas in

Table 2 Distribution of land-use types in the study area

Land use types	Area (%)
High forest	32.24
Agriculture	28.86
Forest Soil (FS)	27.42
FS-Stony	3.52
Coppice forest	3.34
Residence	1.38
Rangeland	0.87
Water	0.83
FS-Erosion	0.44
Stony	0.34
Afforestation	0.26
Sand	0.22
Others	0.28

forest lands were 236358 ha and 338923 ha, respectively. The flat areas in the forest land were found to total 19243 ha. Depending on the alignment of the road network, some of the forest land could be classified under more than one terrain structure.
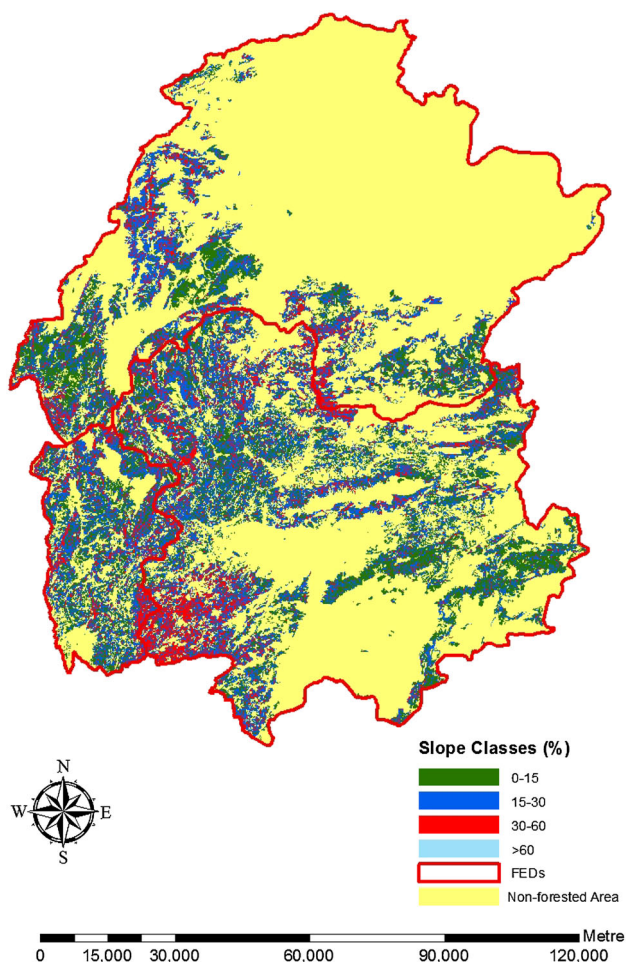
Fig. 4 The ground-slope classes of the forest land in the study area

Fire-access zone widths were computed based on Eqs. 1, 2, and 3 with respect to terrain structures and ground-slope classes (Table 3). For flat areas, FAZ and NFAZ widths were 378–400 m, respectively. Then, fire-access zones were determined for the three slope classes (i.e. steep areas with more than 60 % slope was not considered) based on NFAZ widths. Finally, they were combined to find total accessible areas for each terrain structure.

Table 3 FAZ and NFAZ widths in meters

Slope Classes	Terrain Structures			
	Downhill		Uphill	
	FAZ	NFAZ	FAZ	NFAZ
Low	453	475	324	350
Medium	567	600	283	300
High	1133	1150	227	250

The results indicated that 72.46 and 46.70 % of the downhill and uphill areas in the forest were within the fire-access zones, respectively. It was found that 97.40 % of the flat areas were within the access zones. When combining all three terrain structures, it was found that 69.30 % of the forest land was within the accessible areas, while 30.70 % of the forest was out of the accessible areas (Fig. 5). The accessible and inaccessible areas were also calculated separately for forested areas with different fire-sensitivity degrees. The accessible areas were 69.59, 69.96, and 67.16 % for the forested areas which are sensitive to fires at the first, second, and third degrees, respectively.

Discussion

The methodology and results presented in this study have several potential land and forest fire-management implications. Foremost, the identification of areas outside of hose reach distance also provides a measure of fire-fighting
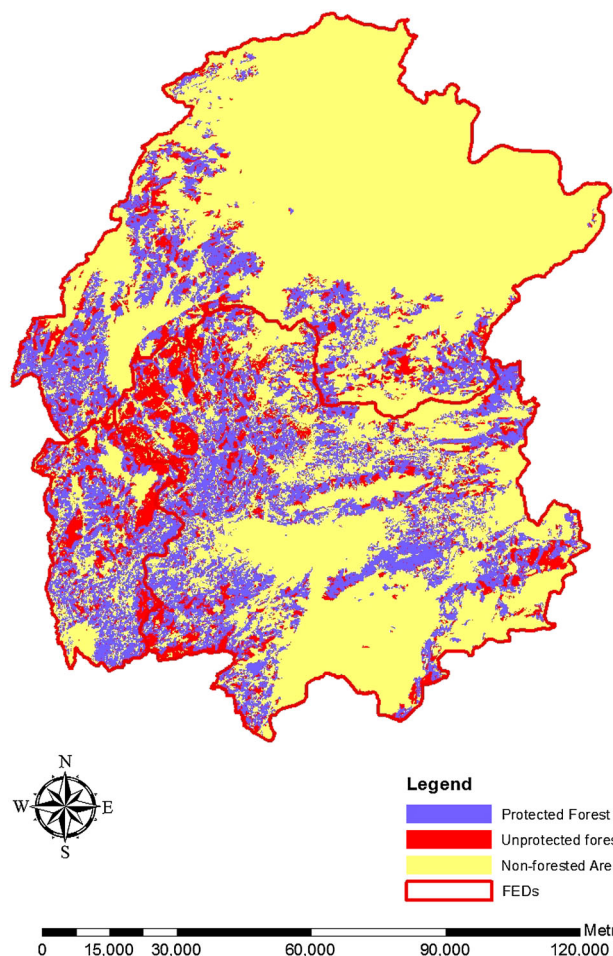
Fig. 5 The accessible (protected) and inaccessible (unprotected) forest lands in the study area

capabilities. Many organizations are limited to fire trucks with hoses for their fire-fighting tools. The results indicated that net fire-access zone width reached up to 600 m on downhill and 300 m on uphill directions. In a similar study conducted by Drosos et al. (2014a), it was reported that firefighting truck with a fire-suppression capacity of 300 m uphill and 500 m downhill adequately covered the forest protection of the West Nestos forest complex in Greece.

The methods presented in this study provide a quantitative measure of the need for additional resources, such as aircraft, to reach areas that are farther away from roads. Besides, some areas also cannot be reached by fire trucks due to terrain structures and ground slope as these topographic conditions affect the effective reach distance of fire-hoses (Böhmer and Dvorscak 2006).

In addition, the identification and mapping of areas that are within the reach of fire hoses provides critical information in determining what portions of the landscape require additional vigilance and attention (Majlingova 2012). For areas within reach distance, land managers have assurance that fires in those areas can be accessed and treated by first-response ground crews using traditional (water and foam) fire-abatement practices (Akay et al. 2012).

Fires in outside areas will require other control methods, such as ground crews constructing fire breaks or creating clearings that are free of fuels such that a fire ceases its progress in these clearings. These efforts will require additional human resources, and importantly, an awareness of increased risk to ground crews. For these reasons, these outside areas should receive extra attention during the fire season so that fire threats are recognized early, and management has sufficient time to amass and direct resources.

If other firefighting vehicles are available that are capable of reaching these outside areas, such as aircraft that can drop foam (slurry) onto an active fire, these supporting vehicles could be readied when monitoring reveals that they may be needed. Besides, using water tanks along the road network might provide extra assistance in fire prevention and suppression activities, especially in mountainous areas where water flows easily downhill and increases the humidity at ground level (Stergiadou et al.2014).

Another application where mapping of areas within and outside of the reach distance of fire hoses may be useful is in the management of the supporting road network. Forest transportation planning and maintenance is a considerable undertaking for many organizations. In order to reduce maintenance needs and save costs, roads may be closed, either temporarily or permanently. In contrast, new roads may have to be constructed in order to support expanded forest operations (Akay et al. 2012). The identification of areas within and outside of reach distance can add support

in deciding whether a road might be closed, without an increase in areas outside of reach distance.

In terms of road construction, road engineers often have some control in the placement of a road, as long as slope and other design requirements are observed. A road engineer might consult a map of areas outside reach distance in considering where to place a new road, such that firefighting efforts are strengthened. Within this process, decision variables such as road density, road spacing, and skidding distance should be accurately determined and final decisions should be made by addressing both forest-fire protection and forest-harvesting purposes (Drosos et al. 2014b).

Conclusions

Along the coastal zones of Mediterranean countries, there are forest areas that have been classified as the first-degree fire-sensitive areas. As a result of forest fires, thousands of hectares of forested area are destroyed annually. In this study, terrestrial FAZs have been generated by determining the effective reach distance of fire hoses from both sides of the roads and considering the technical capabilities of fire-trucks, terrain structure, and ground slope. The results indicate that available ground teams in the study area can access majority of the forest land from the existing road network. However, the road network still needs some improvement since some of the forest lands are not in the forest-access zones. The outcomes of this study provide promising results that GIS-based decision support systems can be effectively used to determine fire-access zones. The next phase of this research should focus on evaluating optimum road spacing by considering the effective reach distance of fire hoses in order to cover all of the forest land, especially in the forested areas highly sensitive to fires. In the future, fire hoses with various diameters, water flows, and nozzle features can be considered in estimating fire-access zone widths.

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