Environ Monit Assess (2012) 184:1391–1407
DOI 10.1007/s10661-011-2049-z

A GIS-based decision support system for determining the shortest and safest route to forest fires: a case study in Mediterranean Region of Turkey

Abdullah E. Akay · Michael G. Wing · Fatih Sivrikaya · Dursun Sakar

Received: 15 January 2011 / Accepted: 5 April 2011 / Published online: 21 April 2011

Abstract The ability of firefighting vehicles and staff to reach a fire area as quickly as possible is critical in fighting against forest fires. In this study, a Geographical Information System-based decision support system was developed to assist fire managers in determining the fastest and the safest or more reliable access routes from firefighting headquarters to fire areas. The decision support system was tested in the Kahramanmaras Forestry Regional Directoratein the Mediterranean region of Turkey. The study area consisted of forested lands which had been classified according to fire sensitivity. The fire response routing simulations considered firefighting teams located in 20 firefighting headquarter locations. The road network, the locations of the firefighting headquarters, and possible fire locations were mapped for simulation analysis. In alternative application simulations, inaccessible roads which might be closed due to fire or other reasons were indicated in the network analysis so that the optimum route was not only the fastest but also the safest and most reliable path. The selection of which firefighting headquarters to use was evaluated by considering critical response time to potential fire areas based on fire sensitivity levels. Results indicated that new firefighting headquarters should be established in the region in order to provide sufficient firefighting response to all forested lands. In addition, building new fire access roads and increasing the design speed on current roads could also increase firefighting response capabilities within the study area.

A. E. Akay (✉) · F. Sivrikaya · D. Sakar
Department of Forest Engineering,
Faculty of Forestry, Kahramanmaras Sutcu
Imam University, 46060 Kahramanmaras, Turkey
e-mail: akay@ksu.edu.tr

M. G. Wing
Department of Forest Engineering,
Resources and Management, College of Forestry,
Oregon State University, Corvallis, OR 97331, USA

Keywords Forest fires · Firefighting teams · GIS · Network analysis · Shortest path · Safest route

Introduction

In recent years, increasing population growth and consumer demand have accelerated the pressures on forests as one of the most important renewable natural resources. Forests are subject to many threats including being cleared for other land use applications, illegal harvesting of trees and other forest resources, and forest fires (Ertugrul 2005). Wildfires seriously damage forests, negatively affect sustainability of forest resources, and result in biological and ecological impacts on forest vegetation (Bilici 2009). Forest fires are major sources of greenhouse gasses such as CO_2

and CH_4 emitted to the atmosphere (Guido et al. 2004). In addition, fire-killed or fire-damaged trees can be more vulnerable to deterioration agents such as insects and fungus, which dramatically reduce the volume and value of forest trees (Akay et al. 2006b, 2007).

Forest fires are considered to be one of the most detrimental factors affecting forest resources throughout the world and, in particular, Mediterranean countries (i.e., France, Greece, Italy, Portugal, Spain, and Turkey) due to their climate and other factors (Demir et al. 2009). In Turkey, there are approximately 5.5 million hectares of forest areas highly sensitive to forest fires along the Mediterranean coastline from its eastern extent to the Marmara region in Turkey (CFE 2008). More than half of these forested lands are considered to be fire-sensitive (Kucuk and Unal 2005). According to annual statistics from 1990 to 2006, an average of 10,000 ha of forest area has been damaged yearly during an annual average of 2,000 forest fire incidents (Akay and Sakar 2009).

A typical firefighting crew is divided into five groups: initial response team, reserved fighting team, mobile team, fire truck team, and aerial support team (Akay et al. 2010). In order to fight forest fires effectively, the arrival time of the initial response team at a fire area should not exceed the critical response time in which the probability of controlling the forest fires rises markedly (GDF 2008). Therefore, it is crucial to determine the optimum route that minimizes the travel time of the initial response team from fire headquarters to the fire areas using firefighting trucks.

In a case of large size fires in Turkey, firefighting teams from other regions are usually called in to assist local firefighting teams. Since they are not familiar with the road network, they may experience problems in traveling efficiently in the woods. Additionally, some of the road sections might be closed due to fire or other reasons during fire incidents. Thus, the optimum route to a fire area should not only be the shortest path but also the safest or most reliable access route given a change in initial network travel pathways. Computer-based methods such as network analysis, linear programming, dynamic programming, and heuristic techniques can be used to systematically search for the optimum route among multiple alternative routes while considering travel constraints (Akay et al. 2006a). A network analysis approach is a potentially powerful approach to solving transportation and routing problems.

Geographical Information System (GIS) technology has been increasingly used in many forestry applications (i.e., forest operations, forest management, watershed management, forest protection, forest transportation, forest fires, etc.) since it provides effective tools to collect, store, manipulate, analyze spatial data, and present descriptive information about them on the maps (Kiser et al. 2005; Sivrikaya et al. 2007; Yuksel et al. 2008; Wing and Tynon 2008; Akay et al. 2008; Gumusay and Sahin 2009; Wing et al. 2010). In recent years, GIS-based decision support systems have been utilized to improve the efficiency of fire management stages including planning, managing, and decision making (Burgan et al. 1998; Sampson et al. 2000; Kucuk et al. 2005). Kucuk and Bilgili (2006) reported that with GIS technology, it is easier, more economical, and faster than traditional approaches in obtaining and analyzing information not only for firefighting activities but also for pre-fire precautionary measures and post-fire operations. Advances in computer and GIS technology have also made it possible to use GIS-based network analysis-based modules such as Network Analyst in ArcGIS 9.2 for solving transportation problems (Sakar 2010).

Previous research has explored the coupling of decision support systems with spatial databases for solving vehicle routing problems (Tarantilis and Kiranoudis 2002; Manussaridis et al. 2007; Keenan 2008). In some cases, research has explored vehicle routing in real-time solutions that allow for routes to be updated dynamically as a vehicle travels across a network (Ichoua et al. 2000; Gendreau et al. 2001; Ghiani et al. 2003). Real-time solutions allow for vehicle movement within a network, changing network pathways or changing conditions along the pathways, and for potential alterations in a destination to be accounted for in the evaluation and selection of a new route.

The application of decision support systems to determine optimal routing or placement of firefighting response teams traveling to a fire area along a road network has been examined by several recent studies. Dimopoulou and Giannikos (2004) developed a GIS-based decision support system to determine how many and what types of firefighting vehicles would be needed to respond to a fire. Vehicle travel speed capabilities along different road types were considered, and the critical time in which a vehicle must arrive at a fire in order to be considered effective were considered. The decision support system also identified where the vehicles should be placed in order to maximize firefighting efficiency. Keramitsoglou et al. (2004) describe development of a decision support system for fire management within Greece that includes a routing portion for vehicle response. Although several variables were described (e.g., type and the condition of the road, population density urban blocks), limited explanation of how variables were evaluated within a routing algorithm were provided. Bonazountas et al. (2007) describe a decision support system for managing forest casualties in which the access time of vehicles to a fire is calculated using GIS network analysis tools. A raster-based road network with impedance values was used to calculate access time including water recharging cycles.

In this study, a GIS-based decision support system utilizing the Network Analyst extension within ArcGIS 9.2 was developed to assist fire managers in determining the fastest and safest travel routes to fire areas. The decision support system was applied in the Kahramanmaras Forestry Regional Directorate (FRD), located in fire-sensitive forests within the Mediterranean region of Turkey. Multiple network analyst simulations were conducted to identify the optimal travel route and associated response times of 20 fire response teams to 15 fire areas that were generated using historical data. The simulations accounted for road surface and condition, sensitivity of forest areas to fire, and scenarios wherein an optimal travel route was not accessible. In addition, the efficiency of using a fire helicopter to transport the initial response team to the fire areas was evaluated.

Materials and methods

Study area

The study area covers six Forestry Enterprise Directorates (FEDs) located in the Kahramanmaras FRD in Turkey: Antakya, K.Maraş, Kilis, Andırın, Dörtyol, and Göksun (Fig. 1). The study area is approximately 2,812,941 ha with approximately 29% covered by forest lands. The bounding geographical coordinates of the study area are 35°46′24.599″ to38°36′31.749″ North latitudes and 35°46′53.539″ to 38°3′26.956″ East longitudes.

The initial response teams are located in 20 different Fire Fighting Headquarters (FFHs) in the study area (Table 1). In order to evaluate the efficiency of initial response teams, potential fire areas were identified within the study area. The locations of previous fires with burned areas of 20 ha or more were obtained from the Kahramanmaras FRD and used to generate potential fire areas (Table 2).

In the Mediterranean coastal area of Antakya FED, a fire helicopter is available to transport the local initial response team (Sahil) to fire areas and to assist with firefighting activities. The helicopter is a Russian-made Mi-8MTV-1 model and is designed to carry up to 20 people and 2.5 tons of water with a special bucket attached underneath. The helicopter can reach flight speeds of 220–230 km/h, with up to 13,000 kg of take-off capacity using a 2200-hp engine (Akay et al. 2010).

GIS database

The GIS-based decision support system developed in this study requires several spatial databases including a road network, land use classes, and fire sensitivity levels. In order to generate these data layers, topographic maps, forest management maps, and fire sensitivity maps were generated and analyzed in ArcGIS 9.2. After

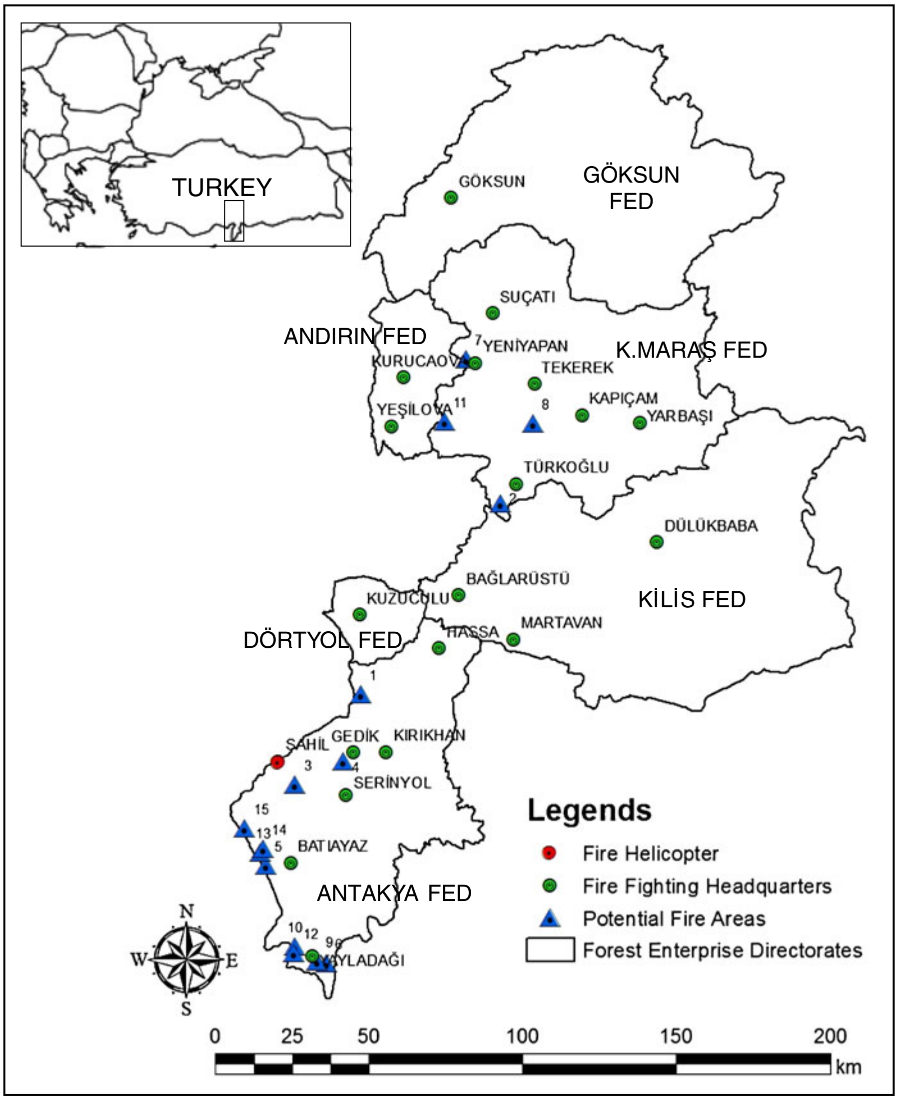

Fig. 1 Forest enterprise directorates, firefighting headquarters, and potential fire areas

producing a road network layer based on 1:25,000 scaled topographic maps, the average travel time of fire trucks (carrying initial response teams) for each road section was estimated and added to the attribute table of the GIS road network database as a new field. The travel time was computed based on road length and average speed of a fire truck, which varies depending on road type and road status (Table 3). The road types in the study area were classified into three groups including asphalt, gravel, and forest roads. The information about road status was obtained from local FEDs, and travel time for each road section was computed using the following formula:

Table 1 Initial response teams in the study area

FED	Initial response teams at FFHs
Antakya	Batıayaz, Gedik, Hassa, Kırıkhan, Sahil, Serinyol, Yayladağı
K.Maraş	Kapıçam, Suçatı, Tekerek, Türkoğlu, Yarbaşı, Yeniyapan
Kilis	Bağlarüstü, Dülükbaba, Martavan
Andırın	Kurucaova, Yeşilova
Dörtyol	Kuzuculu
Göksun	Göksun

$$t_i = \frac{l_i}{v_i} 60 \qquad (1)$$

Table 2 Previous fires greater than 20 ha in the study area

Fire	FED	Area (ha)	Year	Fire cause	Humidity (%)	Temperature (°C)
1	Antakya	25	2000	Accident	80	28
2	K. Maraş	20	2001	Unknown	46	33
3	Antakya	25	2002	Negligence	50	23
4	Antakya	45	2002	Negligence	50	33
5	Antakya	27.5	2005	Negligence	60	14
6	Antakya	20	2007	Negligence	20	35
7	K. Maraş	63	2007	Negligence	40	37
8	K. Maraş	50	2007	Unknown	10	43
9	Antakya	121	2007	Negligence	30–70	40
10	Antakya	46	2007	Negligence	15–25	36
11	K. Maraş	70	2008	Negligence	5	38
12	Antakya	317	2007	Negligence	20–50	35
13	Antakya	200	2007	Negligence	70	12
14	Antakya	574	2008	Negligence	26	7
15	Antakya	263	2001	Negligence	80	28

t_i travel time for road section i (minutes)
l_i length of road section i (kilometers)
v_i average speed of fire truck for road section i (kilometers per hour)
60 used to convert the unit of travel time from hour to minute

The land use map of the study area was generated based on 1:25,000 scaled forest management maps provided by local FEDs. A new data layer indicating forest lands within the study area was generated by reclassifying a digital version of the scaled forest management maps using Spatial Analyst Tools in ArcGIS 9.2. A spatial database of fire sensitivity degrees was produced based on a fire sensitivity map of Turkey obtained from the General Directorate of Forestry (GDF). The spatial databases representing forest lands and fire sensitivity were then combined within a GIS using overlay processing tool to determine the fire sensitivity of forest areas in the study area.

Fire sensitivity level is determined based on fire coefficient which is reflected by number of fire incidents and burned areas per year. Fire sensitivity increases as number of fires and amount of burned areas increase. If fire coefficient is less than 0.35, fire sensitivity level is called as the first degree. If it is 0.35–0.20 and 0.2–0.1, fire sensitivity levels are called as the second and the third degrees, respectively (Kucuk and Unal 2005).

Table 3 Average vehicle speeds (km/h) by road type and status

Road type	Road status		
	Good	Medium	Poor
Asphalt	60	50	40
Gravel	50	40	30
Forest road	30	25	20

Fire coefficient can be computed by using following formulas (Yucel 1998):

$$F_c = N_c + A_c \quad (2)$$

F_c Fire coefficient
N_c Coefficient for number of forest fires
A_c Coefficient for fire burned areas

$$N_c = 100 \times K \times N_f / A_f \quad (3)$$

$$A_c = 100 \times A_b / A_f \quad (4)$$

N_f Average number of fire incident per year
A_f Forested area (hectares)
A_b Average amount of fire burned areas per year (hectares)

Based on long-term statistical fire data collected in Turkey, the value of K in the formula is estimated as 12.74 by dividing amount of fire burned areas by number of fire incidents.

Network analysis

Network analysis is widely used in solving transportation problems that involve the identification

Table 4 Critical response time to forest fires by fire sensitivity level (GDF 2008)

	Fire sensitivity degrees				
	I	II	III	IV	V
Critical response time	20 min	30 min	40 min	50 min	50 min

of an optimum route. In network analysis, links (arcs) and intersection points of links (nodes) combine to construct a network system database that depicts the possible pathways between features across a landscape. In the solution procedure, various parameter values such as length, cost, and travel time are assigned to the network links. The shortest, or optimal, path is selected by searching the route that minimizes the sum of the total link parameter values (Zhan 1997; Akay et al. 2006a).

In this study, the Network Analyst extension of ArcGIS 9.2 was used to develop GIS-based decision support system to assist fire managers in determining the fastest and safest or most reliable access routes to fire areas. In the network analysis database, travel times were assigned to the links representing the road sections in the study

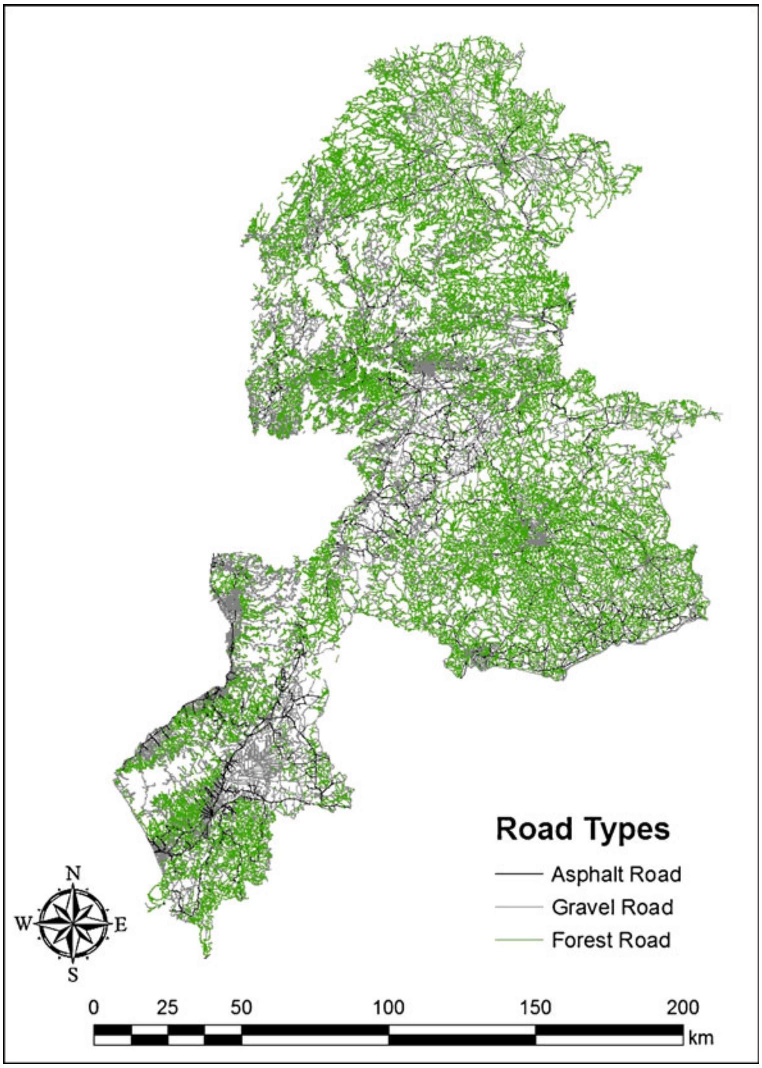

Fig. 2 The road network spatial database within the study area

Table 5 Road network statistics within the study area

Road type	Number of road sections	Road lengths (km)	Road lengths of road status types (km)		
			Good	Average	Poor
Asphalt	11,158.00	4,039.57	4,039.57	–	–
Gravel	69,429.00	25,883.19	13,868.69	8,554.90	3,459.60
Forest Road	46,700.00	32,510.87	13,042.07	18,771.73	697.07
Total	127,827.00	62,433.63	30,950.33	27,326.63	4,156.67

area. Four methods within the Network Analyst extension were implemented to explore routing solutions: new closest facility, new route, new service area, and new origin–destination (OD) cost matrix.

New closest facility

The new closest facility method was used to find the fastest access routes from each initial response team to the potential fire areas in the study area.

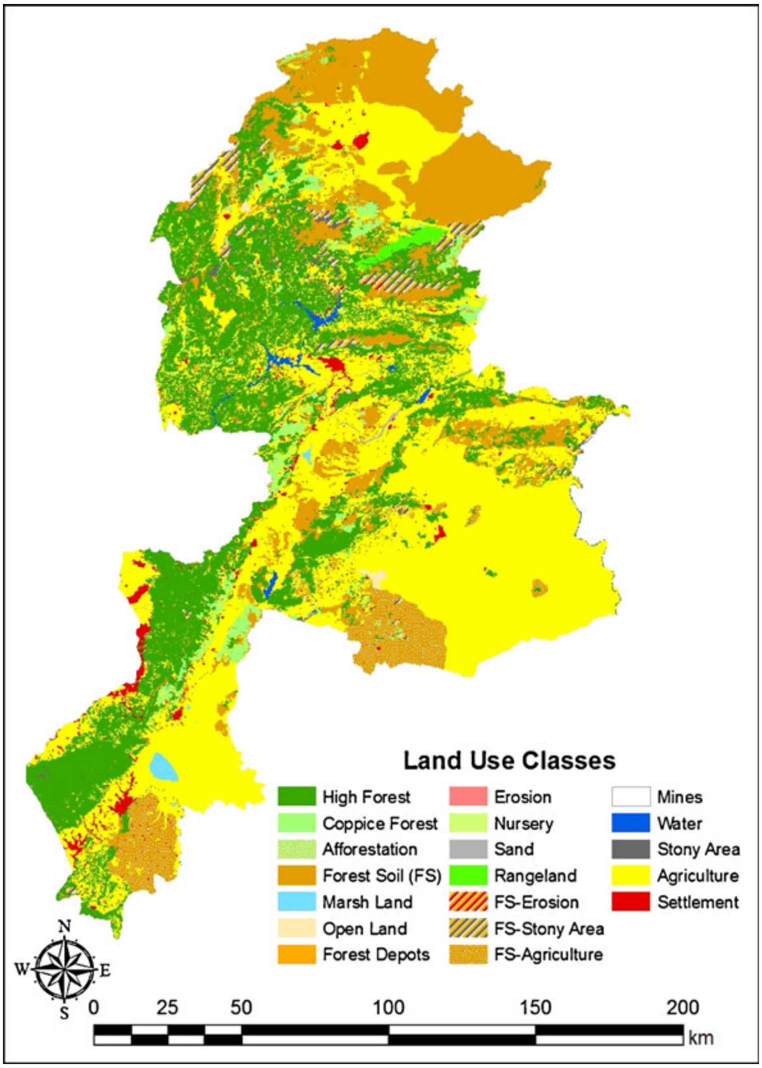

Fig. 3 Land use classes within the study area

Then, the response team with the minimum travel time was determined for each potential fire area. In addition, other initial response teams with the second or third shortest arrival time and their access routes can be identified in a case where an initial response team with the minimum travel time is not sufficient in terms of equipment or number of firefighting personnel.

Considering that some of road sections might be closed due to fire or other reasons such as road maintenance or forest operations, some of the links located on the fastest access routes were hypothetically excluded from the network system by locating barriers on those links. Then, another new closest facility method was implemented to find the fastest and safest or most reliable travel route to the potential fire areas given the newly implemented link restrictions.

New route

The new route method was used to determine the fastest access route from a moving initial response team to a potential fire area in real-time. This capability can be useful in situations where a response team has encountered an optimal route that has become unexpectedly inaccessible due to fire spread or other circumstances. It can also be beneficial for response teams that have strayed from their original route. The new route method takes an updated response team position and then calculates an updated optimal route to a destination. The new route method was applied to investigate not only the fastest but also the safest or most reliable access route in real-time by locating barriers on the links.

New service area

The new service area method was used to evaluate accessible and inaccessible forest areas by the initial response teams according to the critical response time. The critical response time varies depending on the fire sensitivity levels within an area (GDF 2008). Table 4 indicates critical response times which were estimated by General Directorate of Forest based on long-term statistical data collected during forest fire incidents in Turkey. The New Service Area method works similar to a GIS buffer analysis. A service area point is first located in the network system and is considered as a center point from which other portions of the network can be reached given a user-defined total link value threshold. This reachable area comprises the service area. In this study, the locations of the initial response teams are considered as service area points and service areas are then the forest areas that can be reached within the total link value as defined by the critical response time. Therefore, the locations and numbers of initial response teams that are capable of reaching a fire area within the critical response time can be evaluated through this approach.

New OD cost matrix

The distance from any initiation (origin) point in a network system to arrival (destination) points can be quickly computed using the new OD cost matrix method. In this study, the new OD cost matrix method was implemented to estimate the travel time of the initial response team at Sahil

Table 6 Areal distribution of land use classes

Land use classes	Area (ha)	Area (%)
Agriculture	1,213,879.75	43.15
High Forest	738,369.76	26.25
Forest Soil (FS)	484,356.68	17.22
FS-Agriculture	132,824.87	4.72
Coppice Forest	75,350.60	2.68
FS-Stony Area	56,144.27	2.00
Settlement	51,919.94	1.85
Water	14,951.25	0.53
Rangeland	11,839.30	0.42
Marsh land	7,627.72	0.27
Stony area	6,563.46	0.23
FS erosion	6,411.82	0.23
Open land	4,016.73	0.14
Afforestation	3,861.37	0.14
Sand	3,673.06	0.13
Erosion	954.19	0.03
Mines	105.73	0.00
Forest depots	76.84	0.00
Nursery	13.67	0.00

FFH to the potential fire areas when transported by fire helicopter. In the solution process, the flight distance from Sahil FFH to each potential fire area is first determined using the new OD cost matrix method. Then, flight time was computed by using flight distance and average flight speed. Lastly, total travel time was found by adding average flight preparation time onto the flight time. Based on interviews with pilots and technicians in helicopter crews, average flight speed and flight preparation time were estimated at 225 km/h and 10 min, respectively.

Results and discussion

GIS database

Road network

The process of developing the road network spatial database was the most time-consuming aspect of the GIS database development requirements (Fig. 2). A total of 127,827 road sections (links) were manually digitized in generating road network data (Table 5). Results indicated that

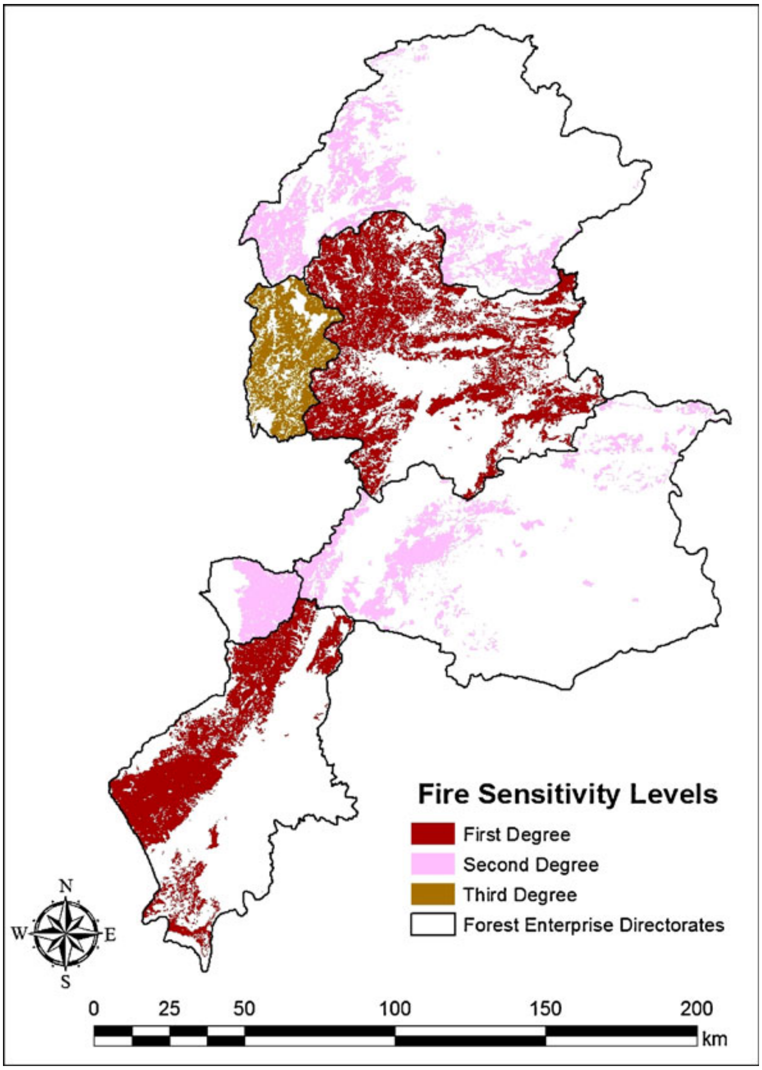

Fig. 4 Fire sensitivity map of forest lands within the study area

total length of the road network was 62,433.63 km with just over half of the total road section lengths (52.07%) being classified as forest road, followed by gravel road (41.46%), and asphalt road (6.47%). In terms of the number road sections, most of the sections were gravel road, followed by forest and asphalt roads. About half of the road network (49.57%) in the study area was found to be in good condition while 43.77% was in average condition. In terms of road types, all of the asphalt roads and over half of the gravel roads (53.58%) were in good condition, indicating that they are capable of providing reliable trafficking. About 57.74% of the forest roads were in average condition while 40.12% were in good condition.

Land use classes

The land use map indicated that there were 19 different land use classes in the study area (Fig. 3). The agricultural lands were the largest land use class, followed by high forest lands (Table 6). The land use classes including high forest, coppice forest, nurseries, and afforestation areas were reclassified as forest lands. Following reclassification, the total forest land area included 817,595 ha, which is about 30% of the study area.

Fire sensitivity level

According to the fire sensitivity map of Turkey, generated based on FED information, the study area consisted of FEDs sensitive to forest fires at the first (Antakya and K. Maraş), second (Kilis, Göksun, and Dörtyol), and third degrees (Andırın). The results indicated that 39.76% of the study area was sensitive to forest fires at the first degree, 55.96% at the second degree, and 4.28% at the third degree. After overlaying the fire sensitivity map and forest land data layer within a GIS, more than half of the forest in the study area was judged to be sensitive to fire at the first (55.56%), followed by the second (34.61%), and the third degrees (9.82%; Fig. 4). It was also found that all of the potential fire areas were located in regions that were judged to be sensitive to forest fires at the first degree.

Table 7 The arrival time (minutes) of initial response teams to each potential fire area

Teams	Potential fire areas														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Bağlarüstü	94	44	127	90	141	161	125	76	155	153	179	158	153	149	163
Batıayaz	91	166	79	61	25	59	247	199	52	45	301	49	37	29	56
Dülükbaba	183	71	216	179	230	250	116	83	244	242	171	247	242	238	252
Gedik	32	126	50	8	78	98	207	158	91	90	261	95	90	86	81
Göksun	282	159	314	278	329	349	102	126	342	341	129	346	341	337	351
Hassa	72	66	105	68	119	139	147	98	133	131	201	136	131	127	141
Kapıçam	181	58	213	176	227	247	59	27	241	240	115	244	239	236	249
Kırıkhan	48	109	61	24	75	95	191	142	89	88	245	92	87	84	97
Kurucaova	256	133	288	252	303	323	47	100	316	315	43	320	315	311	325
Kuzuculu	35	130	79	57	132	152	211	163	145	144	265	149	127	120	110
Martavan	141	90	173	137	188	208	171	123	201	200	225	205	200	196	210
Sahil	43	161	17	39	83	117	242	194	111	109	296	114	63	56	46
Serinyol	56	131	41	23	57	77	212	163	71	69	266	74	69	66	88
Suçatı	219	96	251	215	266	286	39	63	279	278	95	283	278	274	288
Tekerek	182	59	214	178	229	249	40	26	242	241	95	246	241	237	251
Türkoğlu	139	16	171	135	186	206	80	31	199	198	134	203	198	194	208
Yarbaşı	193	74	225	189	240	260	89	56	253	252	145	257	252	248	262
Yayladağı	119	194	107	89	50	11	275	226	4	9	329	10	62	66	81
Yeniyapan	208	85	240	204	254	275	11	52	268	267	68	271	266	263	277
Yeşilova	266	143	298	261	312	332	62	110	326	325	34	329	324	321	335

Network analysis

New closest facility

The fastest access routes for each initial response team to the potential fire areas in the study area were determined using the new closest facility method (Table 7). Results indicated that there is a close relationship between the travel time and road length, as well as between travel time and road types. Initial response teams that reached potential fire areas within the minimum arrival time were identified considering two cases: (1) fastest access route and (2) safest access route.

Figure 5 indicates the fastest access routes to the each potential fire area for the first case. Although the decision support system found the fastest access routes to the potential fire areas, seven of these fires were not accessible by the ground teams within the critical response time (Table 8). Since the potential fire areas were in areas sensitive to forest fires at the first degree, the critical response time was considered to be 20 min.

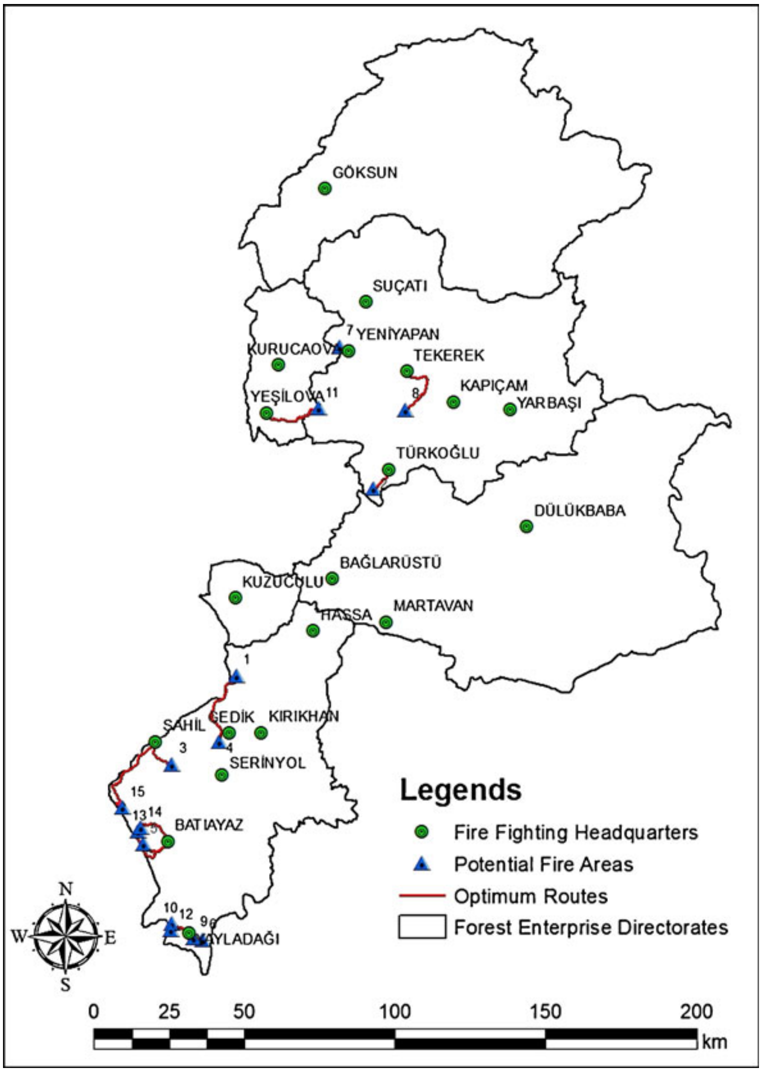

Fig. 5 Fastest access routes from a headquarter location to each potential fire area

Table 8 First initial response teams for each fire area and arrival times for both cases

Fire	Case (without barriers)		Case (with barriers)	
	Initial response teams	Arrival time (min)	Initial response teams	Arrival time (min)
1	Gedik	32.22	Gedik	32.22
2	Türkoğlu	16.18	Türkoğlu	20.51
3	Sahil	16.76	Sahil	16.76
4	Gedik	8.10	Gedik	12.55
5	Batıayaz	24.51	Batıayaz	24.51
6	Yayladağı	10.72	Yayladağı	19.20
7	Yeniyapan	11.44	Yeniyapan	13.42
8	Tekerek	26.08	Tekerek	30.11
9	Yayladağı	4.19	Yayladağı	4.19
10	Yayladağı	8.95	Yayladağı	10.72
11	Yeşilova	33.93	Yeşilova	33.93
12	Yayladağı	9.57	Yayladağı	9.57
13	Batıayaz	36.66	Batıayaz	36.66
14	Batıayaz	29.22	Batıayaz	30.27
15	Sahil	46.48	Batıayaz	55.76

For the second case, barriers were placed in the links of the fastest access route to test the performance of decision support system in determining the safest or most reliable access routes to the potential fire areas. It was found that the response teams that reached the potential fire areas within the critical arrival time were the same as in the first case, except the 15th fire area. However, the number of inaccessible fires within the critical response time increased to eight fires (i.e., including fire number 2). The results from both cases implied that locating a new FFH should be considered by the Kahramanmaras FGD in order to reach potential fire areas within the critical response time.

New route

In the application of the New Route method, the fastest and the safest access routes from a moving initial response team to a potential fire area were evaluated in real-time. Figure 6 indicates the

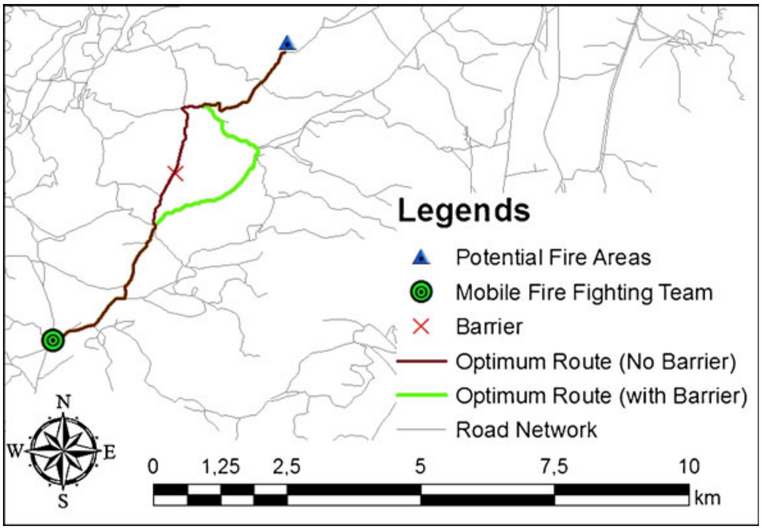

Fig. 6 The optimum routes for a mobile firefighting team to reach a sample forest fire

access routes generated by the decision support system for both cases. The results indicated that the initial response team reached the fire area in 12.67 min in the first case, while arrival time increased by 14.68% for the second case (14.53 min) since the barrier located on a link forced the team to select a different path. This method can be used to provide a fire team with rerouting information in real-time in case selected route is discovered to be blocked. This capability may be advantageous to fire response teams given that forest road networks are rarely static in nature and are potentially subject to rapid change from use patterns, natural disturbances, and maintenance activities. This capability may also be beneficial for situations in which fire response teams find themselves in an unexpected location given difficulties in navigation or as a result of responding to another incident.

New service area

The areas that can be reached by initial response teams within a critical response time were determined by the New Service Area method. Since the study area consisted of areas sensitive to forest

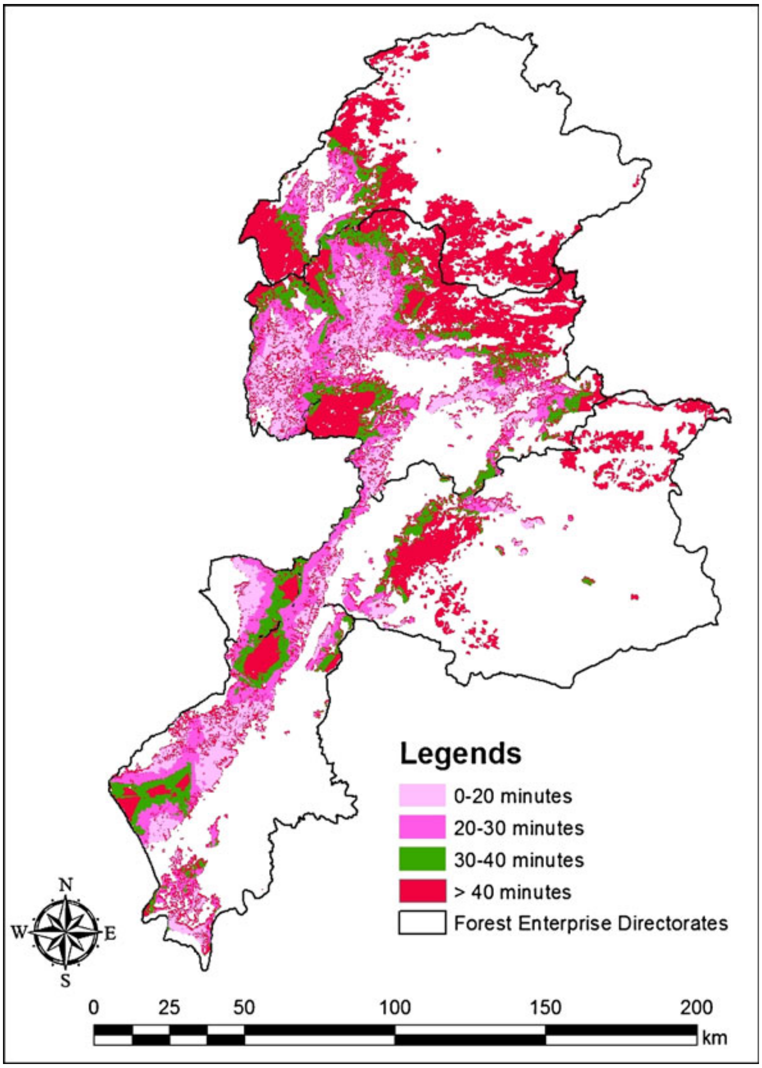

Fig. 7 Forest areas accessible by firefighting teams according to critical response time categories

Table 9 Forest land areas accessible according to critical response time categories

Arrival time	Total area (ha)	Forest area by fire sensitivity degrees (ha)		
		I	II	III
0–20 min	573,977	128,158	36,061	37,995
20–30 min	1,063,664	115,989	45,093	23,498
30–40 min	1,490,186	94,197	43,152	13,653

fires at the first, second, and third degrees, the buffer areas that can be reached through the road network within 0–20, 20–30, and 30–40 min were investigated. Results indicated that the initial response teams could reach 20.40%, 17.41%, and 15.16% of the study area road network within 0–20, 20–30, and 30–40 min, respectively. The remaining road network within the study area (52.98%) could be reached by response teams in times exceeding 40 min.

The GIS tools were used to combine the reachable areas and forest land databases to determine which forest areas could be reached within critical response times (Fig. 7). Considering only the forest areas sensitive to fires at the first degree, we found that the initial response teams can reach

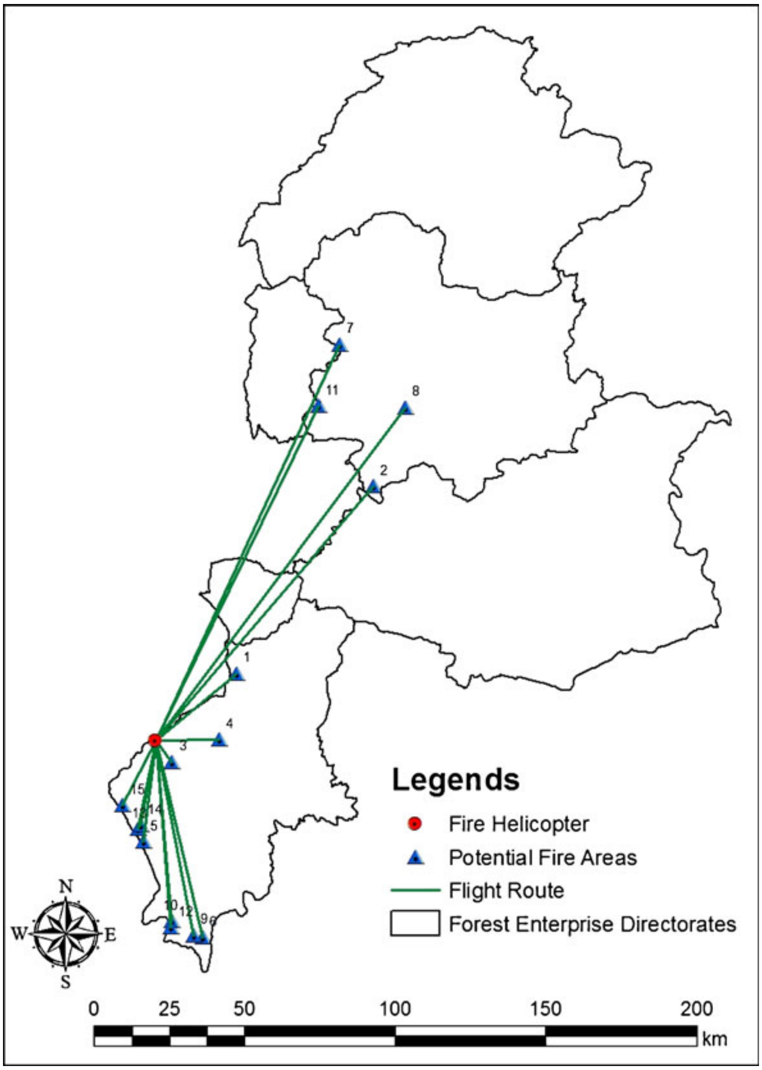

Fig. 8 Flight routes of the fire helicopter to each potential fire area

28.77%, 26.03%, and 21.14% of these areas in 0–20, 20–30, and 30–40 min, respectively (Table 9). The rest of the forest area (24.06%) could be reached by response teams in times exceeding 40 min.

In terms of forest areas sensitive to fires at the second degree, initial response teams can reach 29.24%, 15.55%, and 55.21% of these areas in 0–20, 20–30, and 30–40 min, respectively. The rest of the forest areas (24.06%) could be reached by the team in times exceeding 40 min. Finally, it was determined that the initial response teams can reach almost all of forest areas sensitive to fires at the third degree (95.43%) within the critical response time of 40 min.

New OD cost matrix

The new OD cost matrix method was used to estimate the travel time of the initial response team at the Sahil FFH when traveling to fire areas by fire helicopter (Fig. 8). Results indicated that initial response team cannot reach eight of the 15 potential fire (fire number = 2, 6, 7, 8, 9, 10, 11, and 12) areas within the critical response time of 20 min. In considering initial response teams transported by both fire trucks and fire helicopter, only the 8th and 11th fire areas could not be reached within the critical response time (Table 10). This indicates the relative efficiency of using a fire helicopter in this region for more efficient fire team transportation.

Table 10 Helicopter arrival time for the fire team

Fire	Average flight distance (km)	Arrival time by helicopter (min)
1	34.59	19.22
2	110.63	39.50
3	8.82	12.35
4	20.82	15.55
5	34.00	19.07
6	67.27	27.94
7	144.55	48.55
8	137.73	46.73
9	65.86	27.56
10	60.21	26.05
11	123.12	42.83
12	62.41	26.64
13	30.09	18.02
14	28.78	17.68
15	24.30	16.48

Conclusions

A GIS-based decision support system was applied to determine the fastest and safest access routes from firefighting headquarters to fire areas. The decision support system was evaluated through trials in the Kahramanmaras FRD within the Mediterranean region of Turkey. About 30% of the study area was covered by forest land with 55.56%, 34.61%, and 9.82% of the forest area being subject to forest fires at the first, second, and third degrees, respectively. Having over half of the forest lands highly sensitive to fires indicates the importance of evaluating and planning pre-fire precautionary measures, firefighting activities, and post-fire operations in the region.

The findings indicated that available initial response teams in the study area cannot reach seven out of 15 potential fire areas within the critical response time. When considering an initial response team being transported by fire helicopter and the faster travel times afforded by this methods, only two potential fire areas could not be reached within the critical response time. This finding demonstrates the greater relative efficiencies offered by fire helicopter transportation of firefighting crews over traditional vehicular travel. In the example application, the helicopter-borne crew was able to reach fire areas (fire number = 1, 5, 13, 14, and 15) that were not accessible by the ground-based transportation teams within the critical response time.

The results also indicated that a GIS-based decision support systems can be effectively used to assist fire managers in directing mobile firefighting teams to potential fire areas in real-time. The network barriers were located in one of the fire transportation scenarios to simulate the influence of potential road closures encountered during a crew transport to a fire incident. This application demonstrated that the decision support system can be used to not only determine the fastest access route but can also assist firefighting crews to adjust to unforeseen circumstances and identify a safer and more reliable route should conditions merit.

It was determined which forest areas could be reached by fire response teams within the critical response time considering the locations and numbers of existing response teams in the region. When considering only the forest areas sensitive to fires at the first degree, it was found that about 71.23% of these areas could not be reached by the response teams within the critical response time requirement. The results indicated that initial response teams could not reach about 70.76% of the forest areas sensitive to fire at the second degree within the critical response time. In the case of forest areas sensitive to forest fires at the third degree, only 4.57% of the area was not accessible within the critical response time.

Considering that most of the forest in the study area (90.17%) was sensitive to fire at the first or second degree, the relatively large area considered inaccessible in the study may be the cause for concern for firefighting activities within the study area. The results suggest that new FFHs should be established in the region. Other potential solutions include building new roads or increasing the design standards of existing roads, such that higher travel speeds can be attained by firefighting response vehicles. Some suggestions for future research include investigating optimum road density and location for fire accessibility purposes and the costs of reengineering current forest roads to increase their design standards, especially within forest areas of high fire sensitivity. Besides, the effects of wind speed and wind direction at the time of fire incidents should be addressed in future studies.

Acknowledgements This study is funded by The Scientific and Technological Research Council of Turkey (TUBITAK) with the project number 109O028.

References

Akay, A. E., Erdas, O., Kanat, M., & Tutus, A. (2007). Post-fire salvage logging for fire-killed Brutian Pine (Pinus brutia) Trees. *Journal of Applied Sciences, 7*(3), 402–406.

Akay, A. E., Erdas, O., & Karas, I. R. (2006a). Using GIS and optimization techniques in selecting forest road alignment with minimum sediment yield. First Remote Sensing and GIS Symposium, 27–29 November, ITU, Istanbul, p. 10.

Akay, A. E., Erdas, O., Reis, M., & Yuksel, A. (2008). Estimating sediment yield from a forest road network by using a sediment prediction model and GIS techniques. *Building and Environment, 43*(5), 687–695.

Akay, A. E., & Sakar, D. (2009). Using GIS based decision supporting system in determining optimum path that provides the transportation to fire zone at the shortest time. The Camber of Turkish Engineers and Architectures. The Congress of Geographic Information Systems. 02–06 November. Izmir, Turkey.

Akay, A. E., Sessions, J., Bettinger, P., Toupin, R., & Eklund, A. (2006b). Evaluating the salvage value of fire-killed Timber by helicopter-effects of time since fire and yarding distance. *Western Journal of Applied Forestry, 21*(2), 102–107.

Akay, A. E., Sivrikaya, F., & Sakar, D. (2010). Evaluating the efficiency of fire helicopter located in Arsuz-Antakya in firefighting activities. The 1st International Turkey & Japan Environment and Forestry Symposium. 2–5 November, Trabzon, Turkey.

Bilici, E. (2009). A study on the integration of firebreaks and fireline with forest roads networks and it's planning and construction (A case study of Gallipoly National Park) Istanbul University. *Faculty of Forestry Journal Series: A., 59*(2), 86–102.

Bonazountas, M., Kallidromitou, D., Kassomenos, P., & Passas, N. (2007). A decision support system for managing forest fire casualties. *Journal of Environmental Management, 84*(4), 412–418.

Burgan, R. E., Klaver, R. W., & Klaver, J. M. (1998). Fuel models and fire potential from satellite and surface observations. *International Journal of Wildland Fire, 8*(3), 159–170.

CFE (2008). The chamber of forest engineers' commission report on forest fire in serik and tasagil forest enterprise directorates of Antalya Forest Regional Directorate on July 31st–August 4th 2008. The Chamber of Forest Engineers. Ankara, p. 9.

Demir, M., Kucukosmanoglu, A., Hasdemir, M., Ozturk, T., & Acar, H. H. (2009). Assessment of forest roads and firebreaks in Turkey. *African Journal of Biotechnology, 8*(18), 4553–4561.

Dimopoulou, M., & Giannikos, I. (2004). Towards an integrated framework for forest fire control. *European Journal of Operational Research, 152*, 476–486.

Ertugrul, M. (2005). The situations of forest fires in the world and in Turkey. *ZKU Bartin Faculty of Forestry Journal, 7*(7), 43–50.

GDF (2008). Fire action plan. General Directorate of Forestry. Kahramanmaras Forest Regional Directorate, Kahramanmaras, p. 106.

Gendreau, M., Laporte, G., & Semet, F. (2001). A dynamic model and parallel tabu search heuristic for real-time ambulance relocation. *Parallel Computing, 27*, 1641–1653.

Ghiani, G., Guerriero, F., Laporte, G., Musmanno, R. (2003). Real-time vehicle routing: Solution concepts, algorithms and parallel computing strategies. *European Journal of Operational Research, 151*, 1–11.

Guido, R., Van derr Werf, J. T., Randerson, G., James Collatz, L., Giglio, P. S., & Kasibhatla, A. F. (2004). Continental-scale partitioning of fire emissions during the 1997–2001 El Nino/La Nina period. *Science, 303*, 73–76.

Gumusay, M. U., & Sahin, K. (2009). Visualization of forest fires interactively on the internet. *Scientific Research and Essay, 4*(11), 1163–1174.

Ichoua, S., Gendreau, M., & Potvin, J. Y. (2000). Diversion issues in real-time vehicle dispatching. *Transportation Science, 34*, 426–435.

Keenan, P. (2008). Modelling vehicle routing in GIS. *Operational Research, 8*(3), 201–218.

Keramitsoglou, I., Kiranoudis, C. T., Sarimveis, H., & Sifakis, N. (2004). A multidisciplinary decision support system for forest fire crisis management. *Environmental Management, 33*(2), 212–225.

Kiser, J., Solmie, D., Kellogg, L., & Wing, M. G. (2005). Efficiencies of traditional and digital measurement technologies for forest operations. *Western Journal of Applied Forestry, 20*(2), 138–143.

Kucuk, O., & Bilgili, E. (2006). The conveyance of fire behavior characteristics into practice by using geographical information systems (GIS): A case study in Kastamonu. Gazi University. *Faculty of Forestry Journal, 6*(2), 262–273.

Kucuk, O., Bilgili, E., & Durmaz, B. D. (2005). Importance of fuel maps in determination of fire potential. Süleyman Demirel University. *Faculty of Forestry Journal, A*(1), 104–116.

Kucuk, O., & Unal, S. (2005). Determination of fire sensitivity degree: A case study in Tasköprü State Forest Enterprise. Kafkas University. *Faculty of Forestry Journal, 6*(1–2), 28–34.

Manussaridis, Z., Mamaloukas, Ch., & Spartalis, S. (2007). A VRS dimension framework for effective DSS design. *Applied Mathematical Sciences, 1*(42), 2079–2090.

Sakar, D. (2010). Determining the optimum route providing the fastest transportation to the fire areas by using GIS based decision support system. MSc Thesis. KSU, Faculty of Forestry, Kahramanmaras. Turkey, p. 81.

Sampson, R. N., Atkinson, R. D., & Lewis, J. W. (2000). Mapping wildfire hazards and risks. Food Product Press, 10 Alice Street, Binghamton, NY 13904–1580 USA, p. 343.

Sivrikaya, F., Keles, S., & Cakir, G. (2007). Spatial distribution and temporal change of carbon storage in timber biomass of two different forest management units. *Environmental Monitoring and Assessment, 132*, 429–438.

Tarantilis, C., & Kiranoudis, C. T. (2002). Using a spatial decision support system for solving the vehicle routing problem. *Information and Management, 39*, 359–375.

Wing, M. G., Eklund, A., & Sessions, J. (2010). Applying LiDAR technology for tree measurements in burned landscapes. *International Journal of Wildland Fire, 19*, 104–114.

Wing, M. G., & Tynon, J.F (2008). Revisiting the spatial analysis of crime in National Forests. *Journal of Forestry, 106*(2), 91–99.

Yucel, M. (1998). Computing fire sensitivity of forest regions. *The Journal of Forest Engineering, 7*, 22–25.

Yuksel, A., Akay, A. E., & Gundogan, R. (2008). Using ASTER imagery in land use/cover classification of Eastern Mediterranean landscapes according to CORINE land cover project. *Sensors, 2008*(8), 1237–1251.

Zhan, F. B. (1997). Three fastest shortest path algorithms on real road networks: Data structures and procedures. *Journal of Geographic Information and Decision Analysis, 1*, 70–82.