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Expanding the Accessible Forest Areas by Improving Forest Road Standards and Utilizing Mobile Fire-fighting Teams

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Abstract

In Turkiye, insufficient technical standards of the forest roads limit the speed of the fire truck, leading to increase in the arrival time of the initial response team to the fire areas. Improving forest road standards will increase the design speed and expand the accessible forest areas within the critical response time. In this study, the effect of improving forest road standards on expanding accessible forest areas was investigated. Considering the forest areas in Antalya Forestry Regional Directorate in Turkiye, accessible areas by the stationary initial response teams (103) and mobile teams (71) were determined from the existing road network, and then, the possible increase in the accessible forest areas was investigated when the road standards are improved. Within the scope of the study, the impact of mobile teams used in emergencies on forest areas reached during the critical response period was also evaluated. According to the results, in the scenario where current road standards and stationary teams were evaluated, it was determined that only 59.54% of the forest areas could be reached by initial response teams during the critical response time. When the road standards were improved, this rate increased to 71.69%. On the other hand, when the current road standards and stationary and mobile teams were evaluated together, it was determined that initial response teams could reach 70.40% of the forest areas during the critical response time, and if road standards were improved, this rate increased to 78.17%. Also, utilizing mobile teams increased the accessible forest areas within the critical response time by 9.03%. The results have shown that improvements in road standards and the presence of mobile teams have a very effective role in combating forest fires.

Keywords: Wildfires, forest roads, stationary and mobile team, network analysis, GDF, GIS.

1. Introduction

Forest fires, approximately 95% of which are estimated to be human-caused, seriously damage forest ecosystems and threaten the sustainability of forest resources (Bilici, 2009; Demir et al., 2009). Besides, fire-damaged trees become more vulnerable to agents such as insects and fungi (Akay et al., 2007). The Mediterranean region is susceptible to forest fires because of the tree species and the dry weather conditions (Eker and Abdurrahmanoğlu, 2018). In Türkiye, 12 million hectares of forest area along the coastline, starting from the east of the Mediterranean region and extending to the Marmara region, is susceptible to fire (CFE, 2008). According to the statistical results for forest fires obtained from the General Directorate of Forestry (GDF) between 2004 and 2021, Antalya (5027.90 ha), Muğla (3086.26 ha), İzmir (1257.65 ha), Mersin (1088.95 ha) and Kahramanmaraş (941.09 ha) Regional Directorates of Forestry are in the top five in the rankings according to annual averages on an area basis (GDF, 2022).

In order to effectively respond to forest fires, the time for first responders to reach the fire area should not exceed the critical response time. Otherwise, forest fires could grow and turn into natural disasters. The critical response time is defined as the time when the probability of extinguishing forest fires increases significantly and varies depending on the fire sensitivity of the burned area (GDF, 2008). In determining the fire sensitivity rate in forest areas, the number of fires, the ratio of the burned area to the forest area of the enterprise and the fire constant are used (Mol, 1994).

The initial response team is located in throughout the fire season and remains on alert. After receiving a fire call, the initial response team must prepare and move to the fire area immediately. In addition, mobile teams work to fight forest fires in fire-sensitive, dangerous, and risky

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forest areas, and in certain areas where fires occur frequently. Usually, forest areas that initial response teams cannot reach are also managed by a mobile team consisting of 4-5 workers. Mobile teams are deployed in certain places to ensure their control (GDF, 1995).

In recent years, GIS-based decision support systems have been widely used to increase the effectiveness of fighting forest fires (Küçük and Ünal, 2005). Advanced developments in computer and GIS technology enable network analysis-based GIS techniques to solve transportation problems (Akay and Şakar, 2009). Some studies have investigated real-time solutions that enable dynamic updating of alternative routes for vehicles traveling through the road network (Gendreau et al., 2001; Ghiani et al., 2003). Real-time solutions allow vehicle movement on the road network, changing routes or conditions along the road network, and possible changes in the destination to be taken into account when evaluating and selecting a new route.

Akay et al. (2012) developed a GIS-based decision support system that uses the Network Analyst method in ArcGIS software to determine the routes that enable the initial response team to reach the fire area in the fastest and safest way. The results showed that new fire stations should be established in the region in order to intervene in forest areas in a timely manner. Additionally, it has been suggested that the construction of new forest roads in the region could increase the effectiveness of fighting fires. Wang et al. (2014) conducted a study where a model was developed to calculate obstacle-avoiding routes, considering the type of the response team, position of the vehicle, departure time, the topology of the road network, changing availabilities of roads during disasters, and spread of fire as movements of obstacles that block the roads. They stated that the model can be used effectively in determining optimum routes while excluding fire danger zones in the area. Podolskaia et al. (2019) developed a transportation network model that determines the travel time and distance to forest fires using the Network Analyst method. In the study, a fire protection zone map was produced to evaluate road access to the fire area, taking into account three time periods. It has been found that forest fires mostly occur in areas that can be reached within one to two hours.

To improve the effectiveness of firefighting activities, the forest road network in fire-sensitive forests should be carefully evaluated by considering appropriate building, construction, maintenance, and improvement methods (Laschi et al., 2019). In this study, GIS-based network analysis method was used to investigate the increase in the accessible forest areas within the critical response time in the case of the improving forest road standards. Network Analyst methods were used in ArcGIS 10.8 software to determine reachable forest areas.

2. Materials and Methods

2.1. Study Area

Considering the total forest area damaged by forest fires between 2004 and 2020, it is seen that Antalya RDF is the regional directorate with the most burned forest area, with 30144 hectares (GDF, 2020). For this reason, the entire Antalya RDF was chosen as the study area (Figure 1). The study area is approximately two million hectares, 55.43% covered with forest areas. Primary tree species within the borders of the regional directorate are Brutian pine, Cedar, Black pine, Fir, Juniper and other deciduous species. There are a total of 174 firefighting teams, of which 103 are stationary initial response teams and 71 are mobile teams in the Antalya RDF. In addition, 101 fire trucks, 51 pickup trucks, and 30 water tankers are operating in the region. The study also takes into account the mobile teams that are directed to risky areas and kept waiting there on days when there is a fire risk.

2.2. GIS Database

Using the GIS-based network analysis method, digital data layers, including the road network, forest area, and location of first responders, were generated to determine accessible forests during the critical response time. In this context, road network data, stand maps, and forest protection maps obtained from Antalya RDF were recorded in the database as base maps in ArcGIS 10.8.

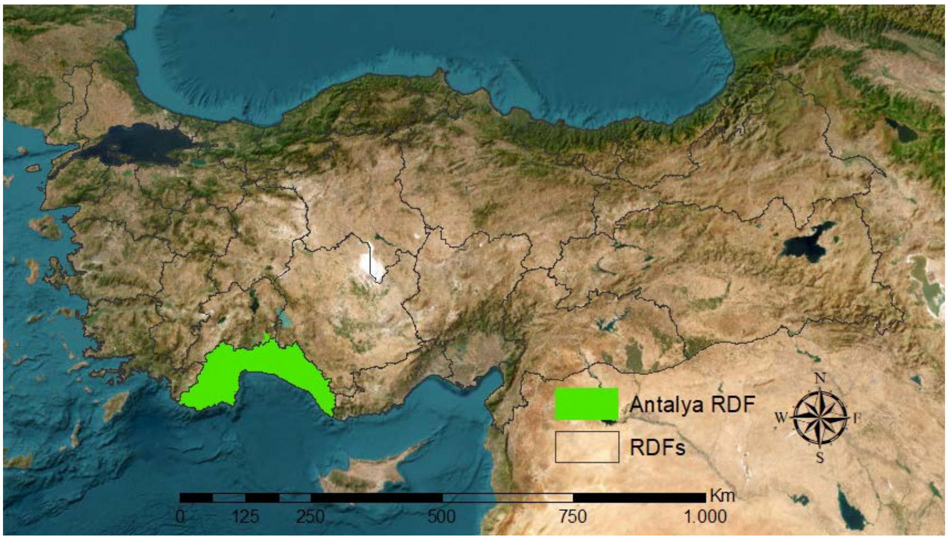

Figure 1. The location of Antalya RDF

2.2.1. Road network

Road network data were obtained from Antalya RDF, missing links and connection errors in the road networks were corrected in the ArcGIS 10.8, and some newly built road sections were digitized based on the recent satellite images. Then, a new field showing the average transportation time of the vehicle carrying the initial response team for each road section in the road network has been added to the attribute table of the road network data. Transportation time is computed depending on the road type, varying road length, and average vehicle speed. Depending on the road superstructure material, road types include asphalt, gravel and forest roads (B-type secondary forest roads). In determining the average vehicle speeds according to road type, vehicle speed information suggested by previous studies (Bilici, 2009; Akay et al., 2012) was taken into account. In light of this information, the average speed of the fire truck for asphalt, gravel, and forest roads was 60 km/h, 50 km/h and 30 km/h, respectively. In the second scenario, since the forest areas that can be reached during the critical response time were determined by taking the improved forest roads into account, the average speed on the improved forest roads (depending on the road improvement construction and road surface construction) was considered as 40 km/h (Akay et al., 2012). The transportation time was recalculated in the improved road network data layer in the second scenario, depending on the road length and the average speed of the vehicle.

The transportation time for each section was calculated using the Field Calculator tool in the Attribute Table with the help of the following formula (Şakar, 2010):

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

As can be seen in Equation 1, ti refers to the total transportation time (minutes) for section i, li refers to the length of section i (km) and vi refers to the average vehicle speed (km/hour) for section i.

2.2.2. Forest area and response teams

The stand types map obtained from the management plans of the Antalya RDF was used to determine the forest areas in the study area. With ArcGIS 10.8 software, a new data layer was generated for only forest areas using the subdivisions designated as forest areas. Digital data layers regarding the initial response teams, including mobile teams, were obtained from Antalya RDF, and checked through field visits. A digital data layer was prepared to show the location of all fire response teams.

2.3. Determination of Accessible Forest Areas

The possible increase in accessible forest areas was then identified for forest roads with improved standards that enable higher vehicle speeds. In the study, the impact of mobile teams on forest areas reached during the critical response time was also evaluated for both situations. In network analysis, alternative routes on the road network can be evaluated depending on various parameter values such as road length, transportation cost, and travel time. The most suitable route can be selected by investigating the route in which the cumulative value of the total link parameter is minimized (Zhan, 1997).

The New Service Area tool under the Network Analyst in ArcGIS 10.8 was used to evaluate reachable forest areas during the critical response time, which varies depending on the fire sensitivity in an area. Antalya RDF has first and second-degree fire sensitive forest areas in the forest fire sensitivity map developed according to the Forest Enterprise Directorates, (GDF, 2012). The critical response times, estimated by GDF based on long-term statistical data collected during the wildfires, are 20 minutes and 30 minutes for first and second-degree fire-sensitive forest areas, respectively (GDF, 2008). In the study, a network database was first produced for the network analysis application; then New Service Area method was applied.

In this method, a service area point is located in the road network system and is considered a center point from which other parts of network can be reached. The locations of the initial response teams represent the service area points, and the service areas represent the forest areas that can be reached within the total link value (i.e., critical response time). The additional forest areas that could be reached by improving road standards were determined by taking the difference between the forest areas accessible by high-standard roads and those accessible by existing roads. Additionally, the impact of mobile teams on accessible forest areas was calculated for both cases.

3. Results and Discussion

3.1. GIS Data Layers

The total length of the road network in the study area was 32618 km. More than half of the roads are forest roads, followed by gravel roads (37.51%) and asphalt roads (5.26%) (Table 1). The total number of sections produced in the road networks was determined as 25406. According to the number of sections, road types are listed as forest road, gravel road and asphalt road. The road network map of the study area is seen in Figure 2.

Table 1. Length information of the roads in the study area

Road type	Number of sections	Road length (km)
Asphalt	1458	1716
Gravel	9976	12234
Forest road	13972	18668
Total	25406	32618

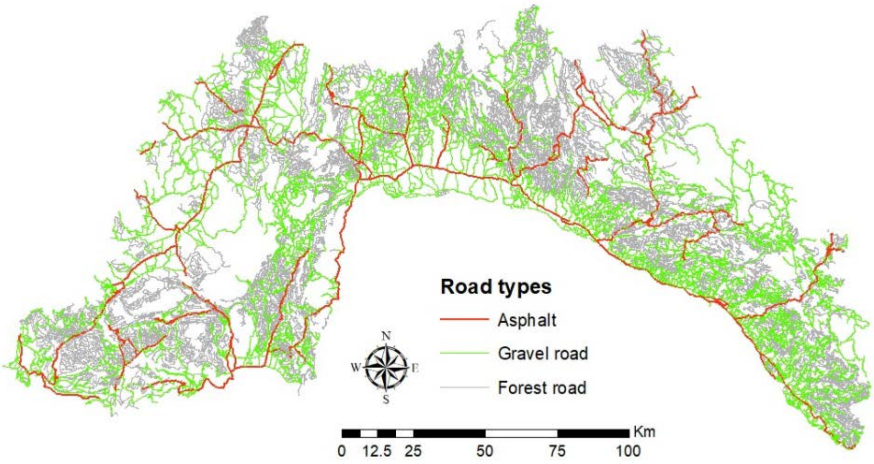

Figure 2. The road network map

The forest area data was generated using the stand type map obtained from the management plans of the Antalya RDF is given in Figure 3. The forest area considered the study area was determined as 1072599 hectares in total. Then, forest areas were classified according to their degree of fire sensitivity. For this purpose, a map for first and second-degree fire-sensitive forest areas in Antalya RDF was produced, taking into account the forest fire sensitivity map developed according to the Forest Enterprise Directorates (GDF, 2012). The forest area within the fire sensitivity degree is given in Figure 4. The results showed that 67.86% of the forests in the study area were sensitive to forest fire in the first degree, while 32.14% were the second-degree fire-sensitive forests. A total of 174 response teams were actively working in the study area. The location of stationary initial response teams (103) and mobile teams (71) in the study area is shown in Figure 5.

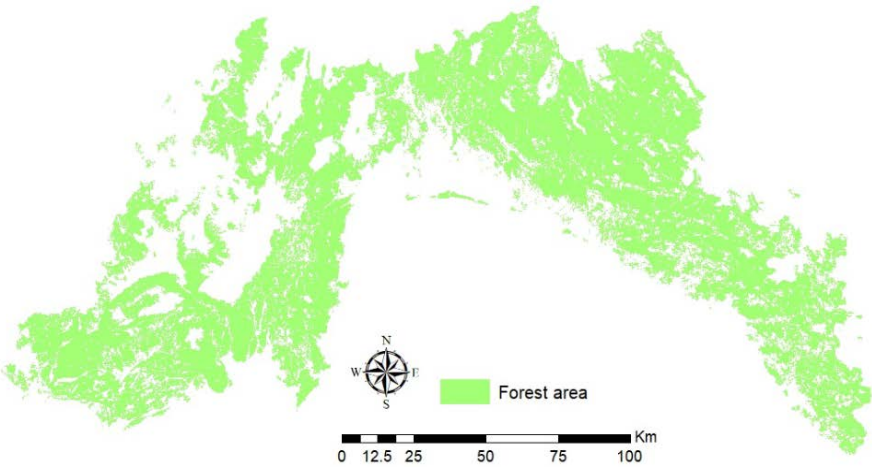

Figure 3. Forest areas in Antalya RDF

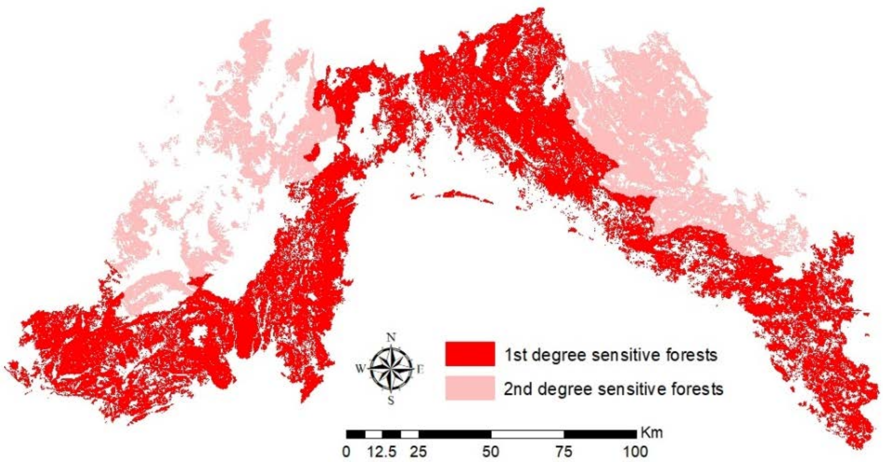

Figure 4. Fire sensitivity map of the forest areas in Antalya RDF

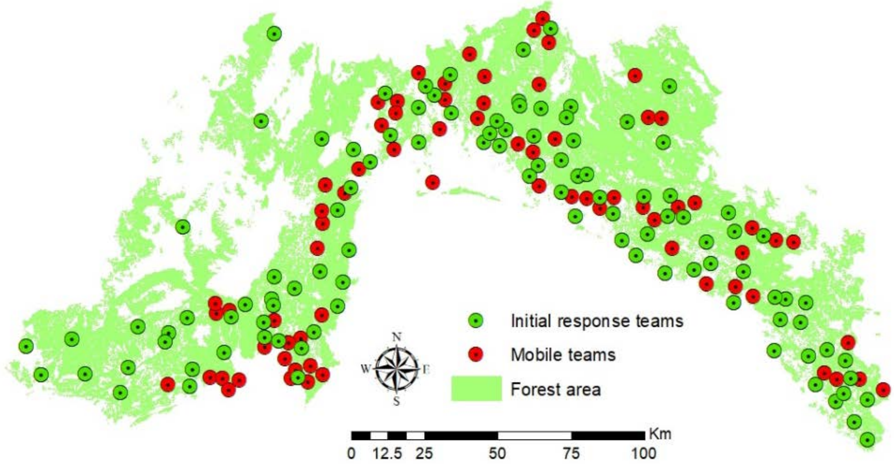

Figure 5. The locations of initial response and mobile teams in Antalya RDF

In developing the network database, a link data layer representing road sections and a node data layer representing the intersection points of these links were produced. Four network databases were produced within the scope of the study. This database were developed for: 1) existing roads and all responding teams, 2) improved forest roads and all responding teams, 3) existing roads and only initial response teams, and 4) improved forest roads and only initial response teams.

3.2. Accessible Forest Areas

3.2.1. Existing road network

When evaluating existing forest roads, using the developed network database, firstly, the forest areas that could be reached only when available initial response teams were taken into account were determined. It was found that 59.54% of the forests within the borders of Antalya RDF could be reached within the critical response time (Table 2) (Figure 6). Considering fire sensitivity, it was determined that 59.30% and 60.06% of first-degree and second-degree sensitive forest areas, respectively, could be reached on time (Figure 7). In a similar study (Şakar, 2010) in which the accessibility of Kahramanmaraş RDF forests located in the Eastern Mediterranean region of Türkiye was evaluated by considering existing forest roads, initial response teams provided intervention to 28.77% and 29.34% of first and second-degree sensitive forest areas, respectively, within the critical response time.

In the second stage, existing forest roads were evaluated by determining accessible forest areas, considering both available initial response teams and mobile teams. The results indicated that 70.40% of the forests within the borders of Antalya RDF could be reached within the critical response time (Figure 8). It was also found that first-degree and second-degree sensitive forest areas that could be accessed on time were 69.18% and 72.97%, respectively. According to these results, the forest areas that could be reached during the critical response time increased by 18.23% if mobile teams were activated. In first and second-degree sensitive forests, the areas that can be reached on time increased by 16.66% and 21.48%, respectively (Figure 9).

Table 2. Forest areas that teams can reach by the existing road network

Teams	Total Area (ha)	Forest Area (ha)	
		The 1st degree sensitive	The 2nd degree sensitive
Stationary Teams	638659.9	431577.2	207082.7
Mobile Teams	755070.7	503499.2	251571.5

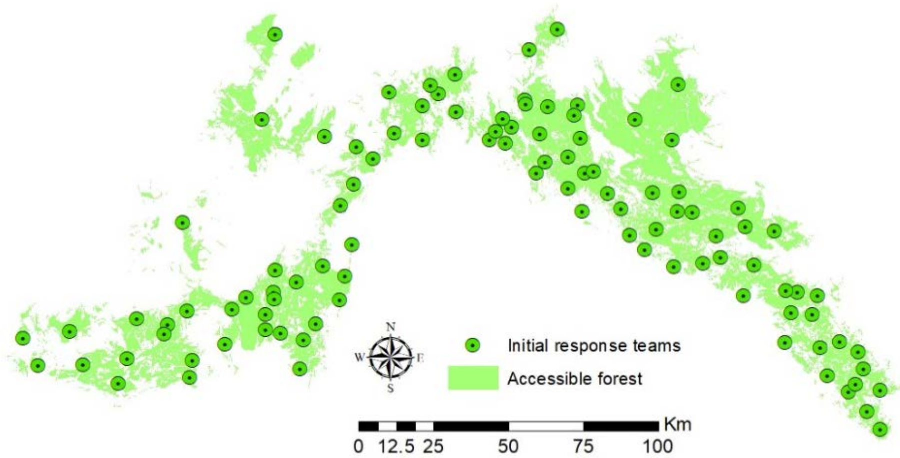

Figure 6. Forest areas reached by initial response teams by existing roads

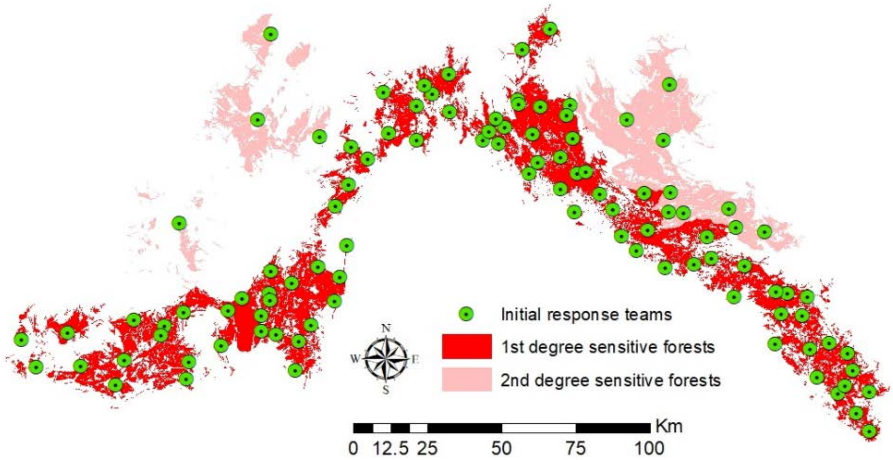

Figure 7. Sensitivity levels of forests reached by initial response teams by existing roads

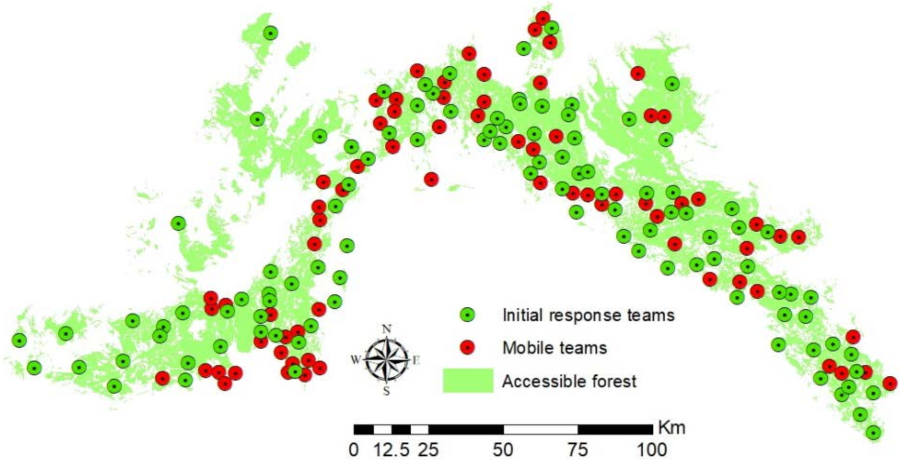

Figure 8. Forest areas reached by initial response teams and mobile teams by existing roads

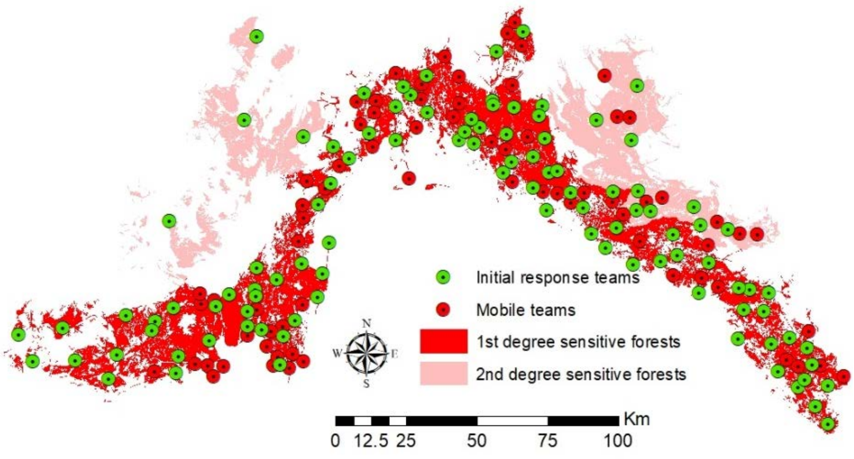

Figure 9. Sensitivity levels of forests reached by initial response and mobile teams by existing roads

3.2.2. Improved road network

For the second scenario, forest roads with improved standards were evaluated to determine the reachable forest areas, taking into account only the initial response teams (Table 3). The results showed that 71.69% of the forests in Antalya RDF could be reached within the critical response time with improved roads (Figure 10). There was a 20.41% increase in access to forests areas compared to existing roads. A study by Zhang et al. (2020) stated that by considering optimal forest road network, the forest areas promptly accessed by the teams were increased from 37.2% to 57.95%. A similar study by Akay et al. (2021) reported that when forest roads are improved, the forest areas accessed during the critical response time increased by 19%. Considering fire sensitivity, it was determined that 69.26% and 76.83% of first-degree and second-degree sensitive forest areas, respectively, could be reached on time (Figure 11).

Table 3. Forest areas that teams can reach by the improved road network

Teams	Total Area (ha)	Forest Area (ha)	
		The 1st degree sensitive	The 2nd degree sensitive
Stationary Teams	768997.6	504102.8	264894.8
Mobile Teams	838432.8	561907.8	276525.0

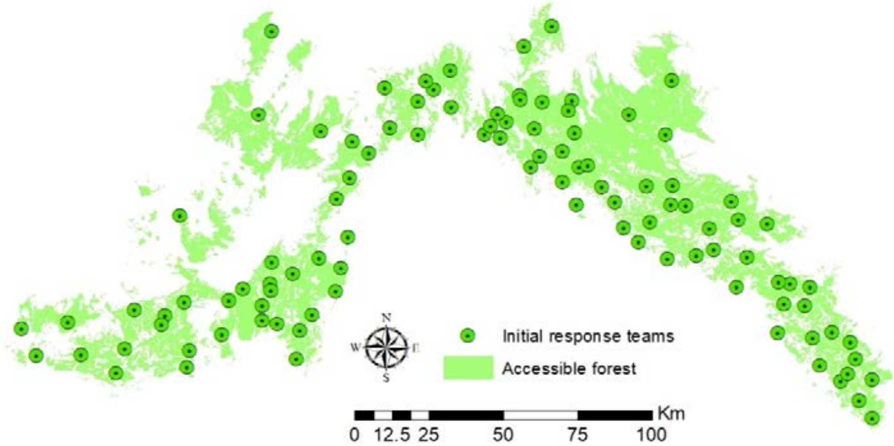

Figure 10. Forest areas reached by initial response teams by improved roads

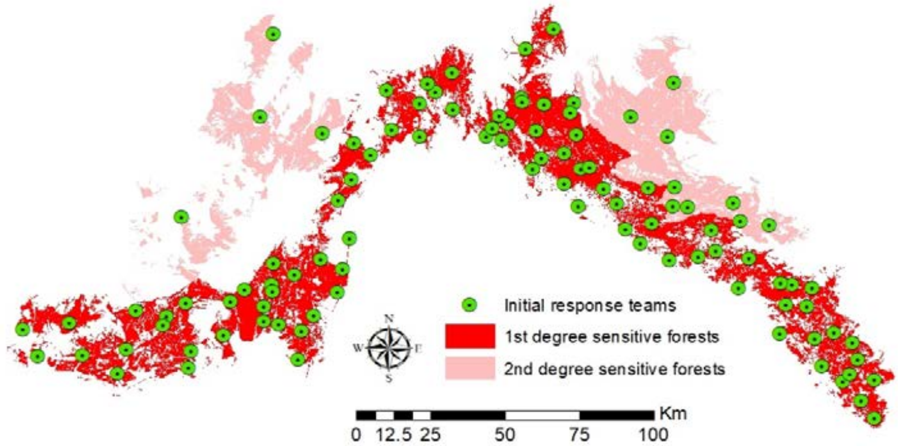

Figure 11. Sensitivity levels of forests reached by initial response teams by improved roads

When evaluating improved forest roads, it was determined that 78.17% of the forests within the borders of Antalya RDF could be reached within the critical response time, considering both initial response teams and mobile teams (Figure 12). These results showed an increase of 11.04% compared to the existing roads scenario. Considering fire sensitivity, it was found that first-degree and second-degree sensitive forest areas that could be accessed on time were 77.20% and 80.20%, respectively. If mobile teams were used, the accessed forest areas within the critical response time increased by 9.03%. In first and second-degree sensitive forests, the areas that can be reached on time increased by 11.47% and 4.39%, respectively (Figure 13).

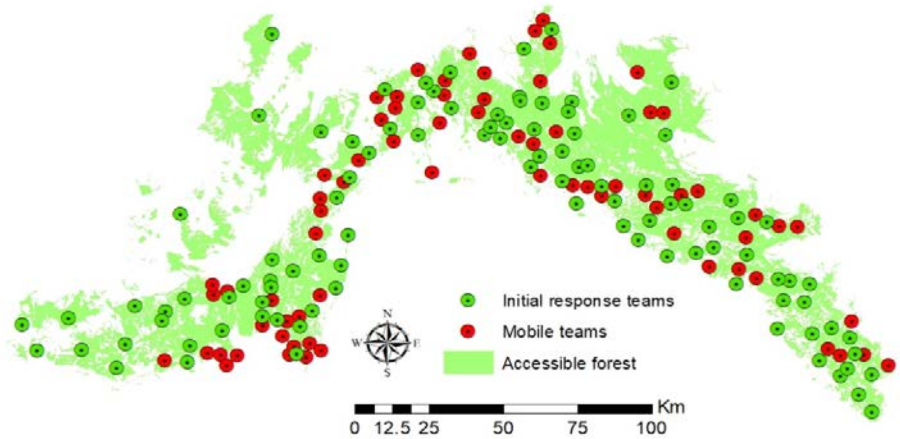

Figure 12. Forest areas reached by initial response teams and mobile teams by improved roads

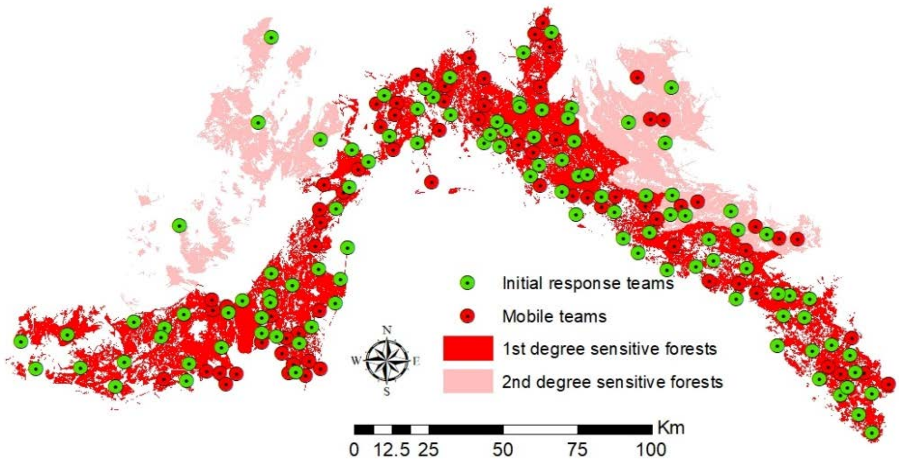

Figure 13. Sensitivity levels of forests reached by initial response and mobile teams by improved roads

4. Conclusions

Forest fires are mostly human-caused events that can result in significant biological and ecological damage to forests and negatively affect the sustainability of forest resources. To minimize the effects of forest fires on forest ecosystems, initial response teams should reach the fire area as quickly as possible via land transportation. Optimizing the locations of initial response teams in firefighting, deploying mobile response teams, improving road density, and increasing the speed design of existing roads significantly increases the effectiveness of fire response. In this study, GIS techniques were used to reveal the importance of employing mobile teams and improving forest road standards in combating forest fires in terms of effective firefighting. The results of the study, in which Antalya RDF was evaluated as the study area, showed that in case of improvement of forest roads, the forest areas that initial response teams can reach during the critical response time were 20.41% more than the forest areas that can be reached considering the current road standards. Besides, the accessible forest areas within the critical response time increased by 9.03% when mobile teams were used. Thus, utilizing mobile response teams and increasing the speed design on existing roads can minimize the time it takes for response teams to reach the fire and increase the accessible forest areas within the critical response time. For future studies, the economic consequences of improving road standards can be investigated by calculating the costs of improving road standards. In addition, the effects of optimizing the locations of initial response teams and building new roads on the arrival time of response teams to the fire scene, especially in fire-sensitive forest areas, should also be evaluated.

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