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Determination of Changes in Forest Road Network in Fire-Affected Areas by UAV*

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Abstract

Forests occasionally confront serious threats due to their dynamic nature. The most dangerous of these threats are forest fires, which seriously harm ecosystems in many nations, including Türkiye. Forest roads are essential to fighting fires and preserving forests because they may physically restrict fires and give firefighters access. Unmanned aerial vehicles (UAVs), which are well-known Remote Sensing (RS) technology, are employed as a key data source in the rapid and accurate analysis of forest ecosystems, with Geographic Information System (GIS). The integration of these technologies facilitates the successful management of forests and fighting fires. This study evaluates the condition of the forest roads damaged by fire in southwest Türkiye, which has a typical Mediterranean climate, pre- and post-fire. Using UAV and satellite imagery was used to examine road parameters, including road length, density, opening-up ratio, and average road slope pre- and post-fire. The results demonstrated that the post-fire forest road network has grown significantly, and the quality of these new roads was low. Post-fire roads are necessary for fighting fires and restoring forests, but their hasty construction can have a detrimental effect on the ecosystem. UAV technology is a very useful instrument, for providing precise and in-depth data for post-fire forest inventory assessments.

Keywords: Forest fire, Forest road network, UAV, Change detection, Remote sensing

1. Introduction

Forests are highly dynamic ecosystems that can face serious threats. Fires are one of the main risks that threaten the survival of forests (Neyişçi, 1988). Besides Türkiye, other countries in Mediterranean climate region such as Spain, Italy, Portugal, Greece, France, Australia, and west cost of the USA are also at risk from forest fires. Türkiye experiences a high number of forest fires annually due to its topography, which creates ideal fire weather, as well as the high human density in coastal areas during fire season (Avcı and Korkmaz, 2021). Türkiye's annual forest fires have led to significant losses of forest areas and natural resources. In addition to destroying trees, these fires can impact on the soil, temperature, and biodiversity of the area (Demir et al., 2009).

Forest roads are an essential part of the infrastructure that keeps forests healthy and helps carry materials, people, and vehicles into and out of the forest, as well as other forest products (Eker and Ada, 2011). Forest roads are essential for managing forest resources and various forestry operations. Forest roads facilitate human access to forests for utilization (Gucinski et al., 2001; Aruga et al., 2005; Marchi et al., 2018; Aruga et al., 2022). Forest roads have various physical, ecological, and aesthetic impacts on forests. Forest roads reduce fire size by creating barriers to their spreads and facilitating firefighting activities, despite causing some harm to the landscape (Covington and Moore, 1992; Forman et al., 2003; Eker and Çoban, 2010). Careful planning is essential for forest roads due to their diverse purposes and implications. Forest roads constructed during and after a forest fire should meet all necessary requirements and be designated as emergency road status (Eker and Çoban, 2009).

Users can obtain decision support through the rapid and accurate analysis of forest ecosystems, achieved by integrating Geographic Information System (GIS) and Remote Sensing (RS) technologies (Koç, 1993; Balcı et al., 2000). GIS is an auxiliary tool that can help the user during the planning and decision-making phases. According to Çoban (2016), one of the most potent features of RS data is its ability to serve as a foundation for GIS. Nowadays, unmanned aerial vehicles (UAVs) are the most widely utilized RS systems. UAVs are used in various industries, including forestry, because they are more affordable and user-friendly than other aerial vehicles (Durgun et al., 2022). Data from UAVs are often utilized in forestry research for monitoring, management, and decision-making purposes (Buğday, 2019).

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This study was conducted in a southwest region of Türkiye that frequently experiences forest fires and has a Mediterranean climate. Satellite imagery was used to assess the pre-fire forest road network within the study area, and orthomosaic data created from UAV images was used to determine the post-fire forest road network. The average road slope, opening-up ratio, road length, and road density in the study area were determined using the RS data for pre- and post-fire. Thus, the changes in the road network of a forest fire-affected area were identified by comparing the data collected pre- and post-fire.

2. Materials and Methods

2.1. Materials

The research area is located in the Isparta Regional Directorate of Forestry in southwestern Türkiye (Figure 1). On August 11, 2021, a forest fire broke out in this area and was suppressed after about 26.5 hours of fighting. A total of 611.7 ha was affected by fire, including 564.9 ha of forest and 46.8 ha of other areas (Onaran, 2024).

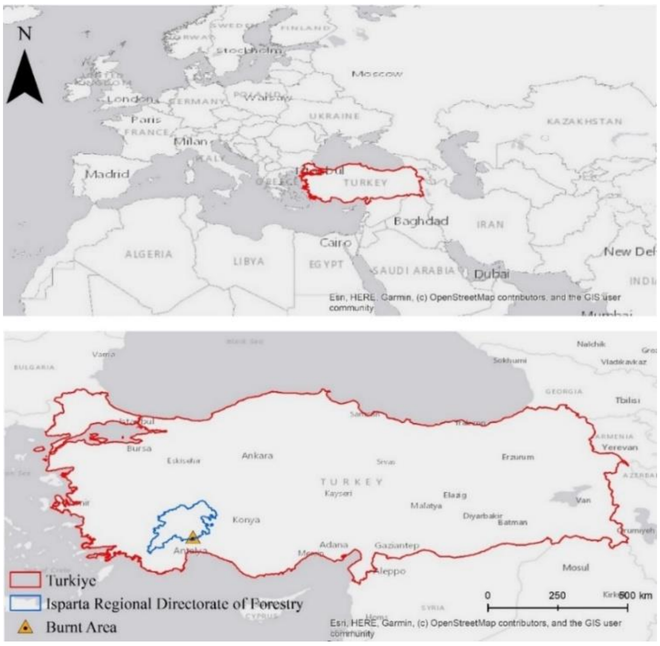

Figure 1. Study area location

Of the 564.9 ha of the forest area damaged by the fire, 409.5 ha were utilized for this study. The study area was covered by Brutian pine (*Pinus brutia* Ten.) prior to the fire (IOBM, 2021). The DJI Mavic Pro 2 UAV was used with a GPS/GLONASS global positioning system, 8 GB of storage, and 31 minutes of flying time for this study. The camera has a CMOS 1-inch sensor with a 77° field of view, 2.8-11 aperture, and 20 MP resolution (DJI, 2018). For geographical analysis, such as generating maps and digitizing forest roads, ArcMap software was used (ArcGIS, 2024). Pix4d "Mapper" photogrammetry software was used to process UAV images and generate orthomosaic imagery. Also, Pix4d "Capture" software was utilized to fly the UAV in compliance with photogrammetric acquisition parameters (Pix4d, 2024). The satellite image of the pre-fire was obtained using Google Earth Pro (GoogleEarth, 2024).

2.2. Methods

The first step of the study was to obtain imagery of the study area. To do that, the UAV flew over only 409.5 ha of the 564.9 ha forest area impacted by the fire due to the inadequate battery capacity of the UAV. Three distinct flight plans were developed and ensuring complete coverage for the study area in each plan to avoid gaps in the mosaic data. For every flight, photographic setting included a 75% overlap ratio and a 90-degree camera angle. A total of 819 images of the research area were captured during three separate flights, totaling 75 minutes.

The collected UAV images were processed using the Structure from Motion (SfM) approach. This approach organizes the positions of the UAV images based on their metadata and aligns them with objects captured in the images. Then, this dataset was used to generate digital elevation models (DEMs), point clouds, and orthomosaics (Snavely et al., 2007). While planning the flights, the goal was to produce orthomosaic data with the same ground sampling distance value; however, this was not achievable because of the variation in topography where UAV employed could not fly parallel to the landforms. Thus, ground sampling distances of the generated orthomosaics ranged from 6 to 10.2 cm. The orthomosaic data were initially reduced (12x12 cm) to ensure that the ground sampling distances value was consistent for all three orthomosaics. Post-fire orthomosaic data was generated by merging the new orthomosaics with the "Mosaic to New Raster" tool within ArcMap 10. 8.2. The borders of the research area were delineated from outside boundaries of the orthomosaic data. After delineating the boundary of the research area, it was used to obtain high-resolution imagery from Google Earth Pro for the pre-fire period (the date of the satellite image is 19/08/2019) (Figure 2).

Once all necessary RS data were acquired, the analysis was carried out. For surface analysis, DEM data were generated from UAV images. The DEM data were combined and reduced in size to ground sampling distance of 1x1 m, similar to the orthomosaic data. The downsizing procedure uses a weighted average value for new pixels to enhance the consistency of geographic analysis results. After generating all data, including DEM and orthomosaics, forest roads were digitized by using these data with ArcMap. forest road density data were derived from the digitized forest road data. It was computed using the general road density formula (Erdaş, 1997; Eker and Çoban, 2010) by dividing road length by the area (m/ha).

Figure 2. The research area's pre- and post-fire views

The opening-up ratio was also determined from digitized forest roads. To do that, the road was buffered with 300m first, and then these buffered areas were divided by the overall study. If the opening-up rate falls between 80% and 100%, it is considered a successful opening-up region (Eker et al., 2010). Additionally, the slope map was derived from DEM and converted to vector data. Then, the vectorized slope map was buffered with 4 m. Forest road was intersected with this buffered slope area using overlay analysis to determine the average slope of the forest roads.

3. Results and Discussion

For this study, DEM data was generated from UAV images. Based on that, the elevation of the study area ranges between 181 and 742 meters. The majority of the research area, almost half of it, is located between 200–399 meters in elevation range. Also, slope and aspect maps of the study area were derived from DEM for the study area (Table 1, Figure 3). Based on slope classes, 48.5% of the area has a larger than 50% slope, 34.9% of the area is in the 20–50% slope range, and 16.6% is in the 0–20% slope range. It indicated that the research area belongs to the high-slope land type (Acar, 1998). The study area's predominant directions were determined to be north (48.7%) and east (34.9%).

Table 2 presents information on the pre-and post-fire conditions of forest roads in the study area, including average road slope, length, density, and opening-up ratio. Figure 4 shows a map of the road network pre-and post-fire. According to preliminary investigations, the study area had 12796.9 meters of roads pre-fire, but post-fire, this number climbed to 55831.4 meters, with 43034.5 meters newly constructed roads. Almost all of the forest roads constructed post fire showed lower geometric and superstructure quality compared to the forest roads that existed pre-fire, according to visual examinations of the mosaic data created from UAV images (Eker and Çoban, 2010; Marchi et al., 2010). However, no comprehensive study has been done on this issue besides the average slope calculation.

Table 1. Study area's geographic features

Elevation Classes (m)	Area (%)	Slope Classes (%)	Area (%)	Aspect Classes	Area (%)
181-199.99	0.4	0-12	8.9	Flat	3.1
200-299.99	23.8				
300-399.99	26.2	12-20	7.7	North	48.7
400-499.99	17.9	20-30	10.8	East	34.9
500-599.99	14.7	30-50	24.1	South	6.3
600-699.99	14.8	50-100	32.5	West	7.1
700-742	2.2	>100	16		

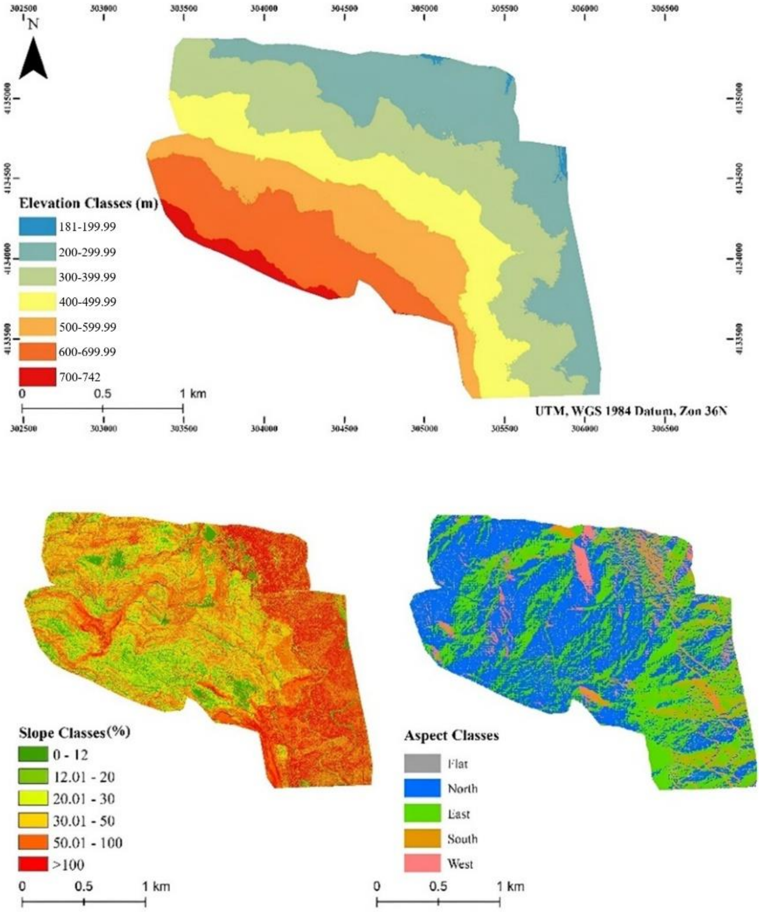

Figure 3. Maps showing the research area’s aspect, slope, and elevation classes

Table 2. Information on the road network pre- and post-fire

Attributes	Unit	Pre-fire	Post-fire
Area	ha	490.5	
Road Length	m	12796.9	55831.4
Road Density	m/ha	26.1	113.8
Opening-up Area	ha	261.4	395.7
Opening-up Ratio	%	53.3	80.7
Average Road Slope	%	10.8	13.8

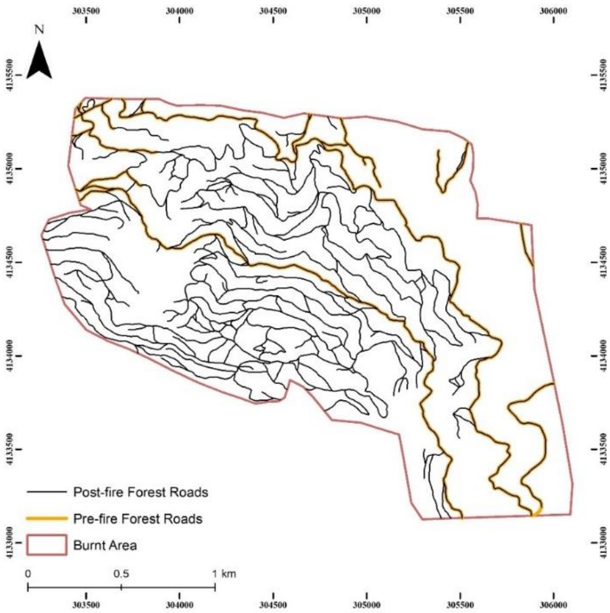

Figure 4. The study area's network of forest roads both pre- and post-fire

The road density in the study area increased along with the overall road length, from 26.1 m/ha pre-fire to 113.8 m/ha post-fire. Even though the expected road density for forestry operations in Türkiye is 20 m/ha (Demir et al., 2009), the road density study area was already higher pre- fire. The 20 m/ha of road density, which seems appropriate in theory, is shown to be insufficient in practice, particularly post-fire when the road density is nearly six times (113.8 m/ha) this value. The opening-up area pre- fire covered by forest roads was 261.4 ha, while it increased to 395.7 ha post fire. As a result, the opening-up ratio rose from 53.3% to 80.7%. This implies that the low rate of opening up pre-fire may have contributed to the time it took (26.5 hours) to contain the fire. It's well recognized that Fires spread more easily when there aren't forest roads (Kaşan, 2009).

The average road slope of the study area pre- fire was 10.8%, and it rose to 13.8% post fire. This result also pointed out that the quality of the forest roads built post-fire are lower than those built pre-fire. Many of these roads are temporary roads and are not used again because they were constructed in the area hastily and without proper planning during and post-fire. Post fire, unnecessary forest roads are constructed at great expense and negatively affect the forest ecology. As a result, to establish the ideal length and density of forest roads, an annual emergency road plan as well as a fire-fighting action plan must be created (Eker and Çoban, 2010).

The results of our study showed similarities with previous research (Eker and Çoban, 2010; Butler et al., 2018; Laschi et al., 2019). The increase in road length post fire reflects how urgently forest roads are needed to ensure forest rehabilitation and lessen the effects of fire. UAVs can be utilized for post-fire inventory (Yuan et al., 2015; Durgun et al., 2022) as well as early forest fire detection (Ghamry et al., 2017). Using the UAV to monitor the post-fire forest road network is practical and efficient for fast and comprehensive inspections of post-fire areas due to its dependability, affordability, and convenience. UAVs offer precise and in-depth data for post-fire inventory, which improves our comprehension of the effects of fires. As a result, using UAV technology in the wake of forest fires can be seen as a crucial instrument for evaluating the damage caused by the fire and assisting in the restoration of the forest.

4. Conclusions

This study aimed to examine post-fire forest roads in a southwest Turkish forest. The findings are significant for understanding the ecological and human impacts of forest fires, as well as for improving rehabilitation efforts following a fire. By comparing the network of forest roads pre- and post-fire, the study effectively illustrates the consequences of fire on forest roads. Following the fire, there were noticeable increases in the length and density of forest roads. These increases emphasize how crucial forest roads are to ensuring forest regeneration and facilitating access for firefighting units.

The analysis showed that the geometric qualities of forest roads built post fire were not as good as those built pre-fire. It means that hastily constructed temporary forest roads lack long-term planning and may severely affect the environment. The data-collecting method with UAVs in this study played a major role in developing the post-fire forest road network inventory. UAVs aid in a better understanding of the consequences of fire and the process of forest reconstruction by providing precise and detailed data in post-fire inventory assessments. In summary, UAV technology is useful for enhancing forest management and firefighting tactics during post-fire activities.

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