Spatial Modeling of Transport and Resources Accessibility for Protecting Forest Ecosystems Against Forest Fires

Abdullah Emin Akay, Ekaterina S. Podolskaia, and Burak Aricak

Abstract

Forest fires are inevitable events that cause negative impacts on forests and threaten the sustainability of forest resources. For effective combating against forest fires, the ground teams should arrive at the fire scene in critical response time in which the possibility of extinguishing the fire is very high. Road networks, including public and forest roads, are the main structures that ensure ground access to the forest resources for management and protection purposes. A network analysis method is effectively used to solve complex transportation problems. Most recent advances in computer technology and geographical information system (GIS) tools with network analysis-based modules have made it possible to develop GIS-based decision support system (DSS) for solving such transportation problems. Network analysis features of proprietary and open source software provide managers with effective methods to define the fastest fire-access route and accessible forested areas by ground teams considering the critical response time. The new route and closest facility methods under Network Analyst tool of ArcGIS software assist fire managers to search for the optimum route that minimizes the travel time of the ground team to the fire. A new service area, which is a well-known method under Network Analyst, is used to evaluate accessibility of the forest areas by the ground teams. This chapter provides a comprehensive review of the previous studies, conducted on the spatial modeling

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M. N. Suratman (ed.), *Concepts and Applications of Remote Sensing in Forestry*,
https://doi.org/10.1007/978-981-19-4200-6_5

of transport and accessibility for the forest resources based on the specific GIS modules.

Keywords

Forest fires · Fire-access route · GIS-based DSS · GIS tools · Closest facilities · New service area

1 Introduction

The public pressure and demands on forest products have increased the pressure on forest resources. The most obvious reflections of the pressure on forest resources are manifested as opening up of forests, illegal cutting, and forest fires. Forest fires are as one of the top severe factors damaging forest resources in many regions in the world due to the existence of fire-sensitive plant species and the arid climatic conditions in summer (Haska et al. 2021). Forest fires lead to reduction in the economic values of the trees, which become more susceptible to insects and fungus after fire damages.

The efficiency of the firefighting activities is of great importance in reducing possible volume and value losses of forest resources due to forest fires. To effectively respond to forest fires, especially in fire-sensitive forests, the transportation time of the ground team to the fire scenes should not exceed the critical response time. For this reason, the optimum route that will enable the ground team to arrive at the fire areas in the shortest time possible after the fire announcement is received should be determined. The network analysis method is widely preferred in solving transportation problems involving the determination of the optimum route that minimizes the travel time of a vehicle between two know points. The advances in computer programming and GIS technology make it possible to use network analysis-based GIS techniques to solve transportation problems. Particularly, the new route, new closest facility, and new service area methods under Network Analyst tool of ArcGIS software provide fire managers with effective tools to search for the optimum route to the fire areas and to determine the forest areas that can be reached within the critical response time (Akay et al. 2012).

The GIS-based DSS using the new route and new closest facilities methods has been examined to determine the most appropriate route that allows firefighting teams to reach the fire areas in the shortest time (Dimitrakopoulos et al. 2011; Akay et al. 2012; Podolskaia et al. 2019a, 2020a, b). In such studies, the effects of variables such as road type, road condition, and population density on the solution phase were evaluated. The decision support systems using new service area have been also used to determine where fire trucks should be placed to maximize firefighting efficiency (Akay et al. 2018; Akay and Taş 2020). In this chapter, a broad overview on spatial modeling of transport and resources accessibility for protecting forest ecosystems against forest fires was presented by reviewing previously conducted studies. Firstly, the studies on the optimum ground access route to forest fires, accessible forest lands by firefighting teams, and their optimal locations are provided, and then the studies on the forest roads as effective infrastructures for fire protection are reviewed.

2 The Optimum Ground Access Route to Forest Fires

For effective firefighting activities, it is crucial that the ground team should arrive at the fire scene within the critical response time. In a study conducted by Bilici (2009), the effects of forest roads along with fires firebreaks and fireline on early access of ground teams to the fire areas were investigated by using the GIS-based network analysis method. Gallipoli National Park in the city of Çanakkale in Turkey was selected as the study area. The network analysis method was used in order to compare the road network without fires firebreaks and fireline and the road network with fires firebreaks and fireline in terms of the fastest access to fire. With this method, it was found that in 27 of 30 inquiries made for 10 potential fire points, the route in the road network with fires firebreaks and fireline was shorter than the route on the road network where fires firebreaks and fireline were not considered. In addition, it has been revealed in the study that the walking distance from the end of the road to the fire point on the route formed as a result of an inquiry was shorter in the road network with fires firebreaks and fireline. When the results of the inquiry were examined, it was determined that fires firebreaks and fireline contributed positively to forest fires at the point of early intervention, and it was revealed that forest roads should be planned together with fires firebreaks and fireline.

Akay et al. (2012) developed a GIS-based DSS to find the optimum route which minimized the transportation time of the ground team from stations to the potential forest fire locations. The application area of the project consists of six forest enterprise directorates located in Regional Forestry Directorate of Kahramanmaraş in Turkey. These Enterprises were classified as sensitive to forest fire and there were 20 fire stations available in the region. In the study, firstly, the digital layers for the road networks (forest roads, rural roads, highways), the fire stations, and previous fire areas (15 fires) were produced by using ArcGIS. Then, network database was generated based on the road layer where travel time of fire truck was assigned to each road section. The travel time was a function of the section length and average truck speed, which varied based on road type and condition. Finally, the optimum route from each ground team to the potential fire areas was found by the new closest facility method (Fig. 1). Besides, inaccessible roads, closed due to fire or some other reasons, were eliminated in the network database, so that the optimum route also provided the safest path. The results indicated that ground teams could not reach 7 out of 15 potential fire areas on time. When the barriers were placed in the database, inaccessible fires increased to eight fires. To increase the efficiency of the ground teams in the study area, it was suggested to locate new fire station, increase the road density, and improve the road standards.

In a study conducted by Podolskaia et al. (2019a), the traveling time of special vehicles (fire trucks, tank trucks, etc.) and the distance from the nearest fire station to a forest fire were estimated using the regional transport model, generated by the

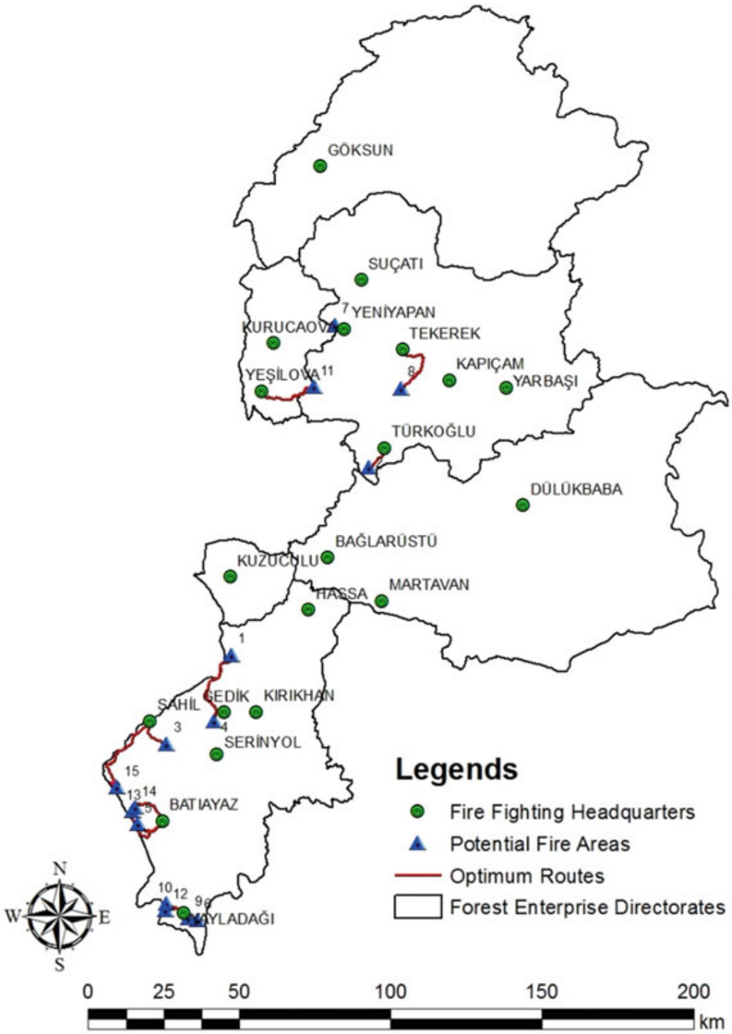

Fig. 1 Optimum routes to potential fire areas (Akay et al. 2012)

Network Analyst tool in ArcGIS (Fig. 2). Based on the dataset of 16 years (2002–2017), the study was conducted in Irkutsk region of Russian Federation where forests are highly sensitive to fires (Goldammer et al. 2003). The GIS dataset was developed to have digital data of necessary layers such as road network, forest glades, fire stations, and forest fire locations. Then, the travel time of the vehicle was computed based on average speed and distance data and then it was assigned to each road section in road network layer. The vehicle speed was computed for each road section based on the road types, elevation data, and terrain slope. The forest fire data detected by MODIS (Moderate Resolution Imaging Spectroradiometer) satellite

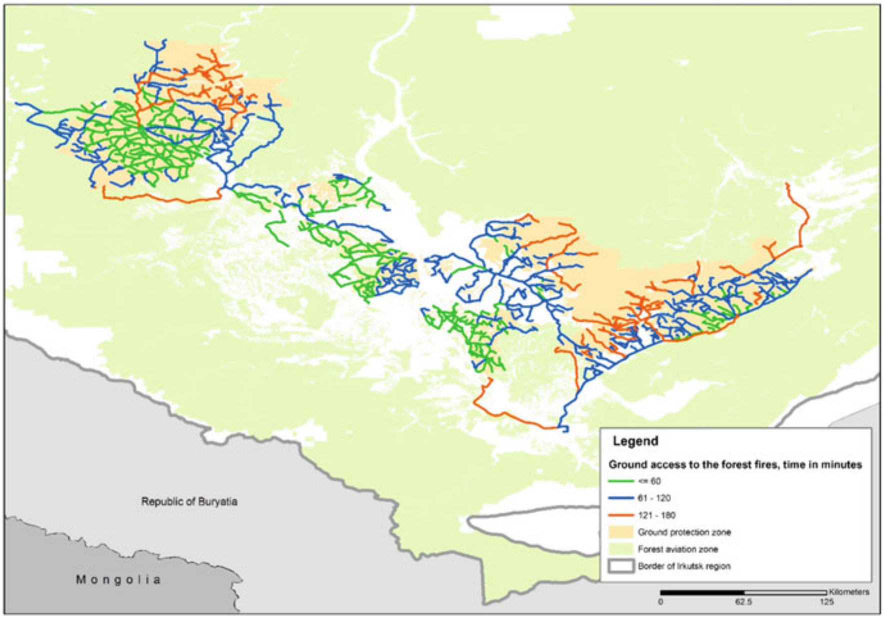

Fig. 2 Optimum routes to forest fires according to travelling time classes (Podolskaia et al. 2019a)

system (2006–2012) was used for model validation. The digital layers for fire protection zones were generated to evaluate the accessibility of ground teams for three time periods (i.e., 1, 2, and 3 h) recommended by the guidelines to ensure the prompt response to forest fires based on the fire danger classes of the forests (Classes I, II, and III). It was found that forest fires are mostly located within the zones of 1 (68.2%) and 2 h (24.3%) availability, while almost all of the fires (98.5%) were accessible in 3 h. The results revealed that the ground protection zone was designed by considering the arrival time of the ground team to the forest fire within 3 h. It was emphasized that the success of the transport value depends on up-to-date spatial data on the road networks and forest glades.

Podolskaia et al. (2020a) developed a GIS technology to determine the optimum ground access routes for special fire vehicles departing from fire-chemical stations and arriving at the detected fire areas. The study was implemented in the central part of the Siberian Federal District in Russian Federation. In the study, the digital data layers for public roads, forest glades, locations of the fire-chemical stations, and forest fires detected by MODIS satellite system (2002–2019) were generated in ArcGIS. Then, a GIS technology consisted of a Python-based set of programs was developed to generate a thematic map of road accessibility to forest fires based on key elements including access time (in hours), road length (in kilometers), and average vehicle speed (in kilometers per hour). The results indicated that most of forest fires recorded in 2002–2019 were accessible by the ground team. However, forest fires located away from the center of the Siberian District were not well accessed by the ground teams. It was also pointed out that forest fires become less accessible when the forest areas get larger.

Some current experience in solving the transport modeling tasks for ground access, mainly in the Russian forestry, is described in a study conducted by Podolskaia (2021a). The geodata sources, data services, and Open Source developments, as well as using various remote sensing data and spatial resolution for the transport modeling, were noted. The projects were done by the scientific and educational institutions in Russia on forest transport accessibility which is a complex issue accenting on the environment and economy. It was suggested that the work should be continued to determine the optimum location for the fire stations, cutting areas, and forest warehouses considering different regions and forest infrastructures. Other potential future studies provided in the study were developing new methods to balance the infrastructural load and natural stability of forest ecosystems.

3 Accessible Forest Lands by Firefighting Teams and Their Optimal Locations

The term “transport accessibility” is widely used in different applications. In the modern forest management worldwide transport logistics of technical means and human resources along the roads to timely reach a place of forest fire or a forest area are among the most challenging ones for forest ecosystem protection and use. Relevant geospatial data for public roads of seasonal and off-seasonal use as well as forest roads and their volume and quality remain essential for the forestry projects (Podolskaia 2021b). From the data management point of view, spatial modeling of transport and resources accessibility depends on the continuous increase of geodata archives and complexity of their practical use.

Implementation of GIS for the ground and aviation transport accessibility and links between fire stations and destinations in the forests at the regional and country levels have been among the research topics already for certain years, especially in the countries covered by forests and having strong and constant forest fire periods. Russia and Turkey are two country examples with such forest fire activity in their warm respective seasons of the year, mainly from spring to autumn.

Ground transport accessibility relates with a question of placing a fire station (a fire-chemical station in Russian forestry terminology) or a logistical center in a particular region. According to the Russian forestry regulations, fire stations and their firefighting brigades are putted in place in the regions to prevent, detect, and limit the spread of forest fires in a timely manner. They are located mainly in the settlements, make a forest fire regional protection network, and include forest enterprises, national parks, and state nature reserves. They have special firefighting equipment, heavy vehicles, and staff.

A research undertaken by Akay et al. (2018) showed that about 1/3 of forest land (Mustafakemalpasa, Bursa, Turkey) was reachable from presently located fire stations in a time frame regulated by the forestry in Turkey. Forest accessibility increased up to 72% when the authors applied a scenario with new fire station location. This scenario includes implementation of GIS-based decision support system (Akay et al. 2012). Fire risk degrees for the fire-sensitive areas have been considered and presented in the cartographic form, including accessibility maps for forest areas with a system of access time frames in the paper (Akay and Taş 2020) for the Yenikoy Forest Enterprise Chief which is closed to the Karacabey Forest Enterprise Directorate (Bursa, Turkey). An important study's output states that about 24% of forest areas were accessible for fire extinguishing works within 30 min.

In Russian Federation forestry transport modeling is a research area for educational and scientific institutions. At the Center for Forest Ecology and Productivity of the Russian Academy of Sciences (CEPF RAS), there is a "Transportation Task" research group which is a part of the Laboratory of Forest Ecosystems Monitoring. Its ongoing activities and projects include the implementation of Open Data and Open Source GIS tools, globally known datasets of OSM and QGIS (Podolskaia 2020, 2021c). In the paper of Podolskaia et al. (2020a), they did a quality control of existing transport systems' datasets by road type (public, forest road, forest glades) and made a comparison with the archived road data.

One of the recent studies was a work done by Podolskaia et al. (2019b) for the large territories of Siberia, the Russian Federation. In order to estimate the spatial location of fire stations the authors suggest three data groups, namely: presence of road network (length, density, and configuration), forest fires detected by satellites, and fire station service areas. GIS analysis with its buffering, allocation, density, as well as geographic and directional distribution, was used as method. The researchers noted that there are other factors and data, and they can certainly influence the fire station's location (access regime of protected areas, use of road depending on the season, zones of protection against forest fires, placement of stations in the most populated areas, etc.). It was advisable to make a fire station placement analysis before and after the fire hazardous season; its results would be of help for retrospective evaluation and forecasting of forest firefighting events.

Accessibility of forest resources presented in the work of Podolskaia et al. (2020c) uses a scenario approach for the territory of regional scale in Russia. A general scheme of methodology including brief data description and operations with data is presented in Fig. 3; it consists of the steps of scenario's preparation, then mapping and analysis.

Novosibirsk region, located in the southwest of the Siberian Federal district of Russian Federation, has been chosen as a key research area because of its developed infrastructure in combination with constant annual forest fire activity; according to the MODIS data it is classified by mixed broadleaf-coniferous forests and non-forest vegetation (Fig. 4). In the study (Podolskaia et al. 2020c) the authors have moved from the previous estimations of forest fires' accessibility (Podolskaia et al. 2019b, 2020b) to the accessibility of forest areas and their resources (Podolskaia et al. 2020c). Spatial transport modeling included creation and use of transport model for two forest management scenarios, namely: without any barriers and with forestries (unit of forestry management in Russia) as barriers; this second one is

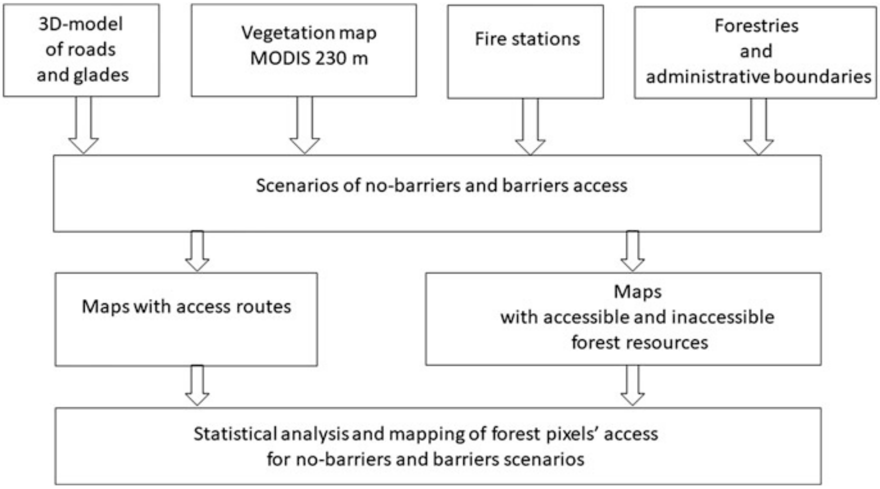

Fig. 3 General scheme of methodology (Podolskaia et al. 2020c)

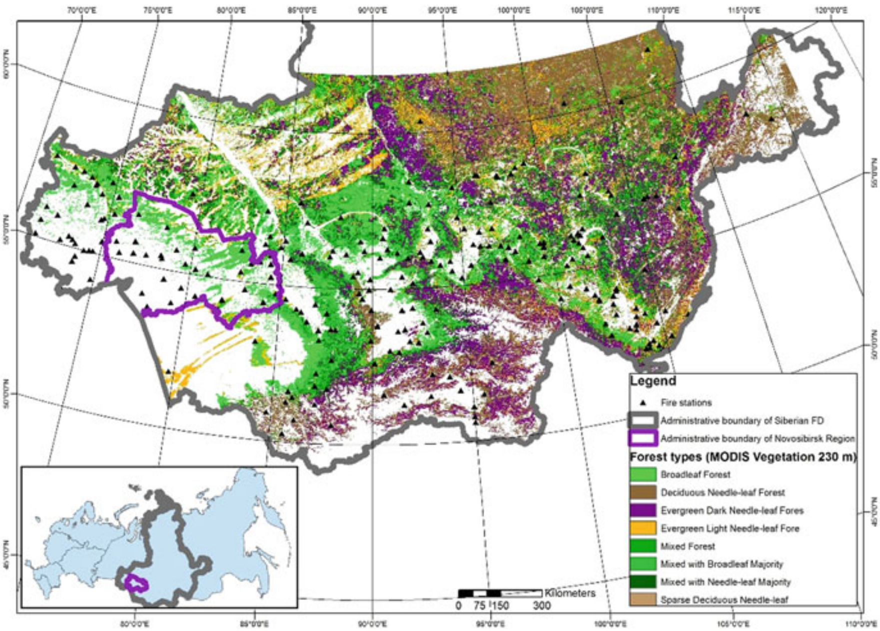

Fig. 4 Key area (Podolskaia et al. 2020c)

spatially presented in Fig. 5. As we can see on the map, the majority of forestries have at least one fire station within their borders.

In that study, the location of existing fire stations has been evaluated under the 3 h condition which is an actual critical response time to access forest fires by ground

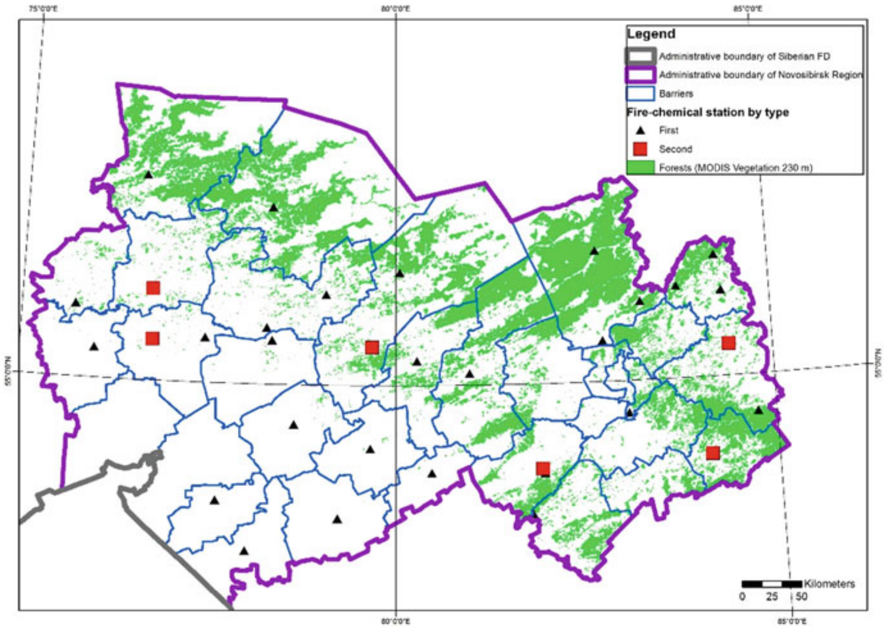

Fig. 5 Fire stations and forests as barriers within Novosibirsk region (Podolskaia et al. 2020c)

technical means in Russian forestry. Fire stations were used as starting points of move along the roads. By implementing this relatively strict time limit for the "no-barriers" scenario, the authors noted that there were about 17% of inaccessible forest areas (namely, forest pixels of MODIS satellite coverage); about 14% of areas were reachable within more than 3 h and 20%—within an hour (Fig. 6). Quantitative results confirmed that forest management scenario of "no barriers" is more promising than a scenario with barriers. The authors detailed that up to 83% of forests (MODIS pixels) of Novosibirsk region were reachable by moving along the roads of different types in "no-barriers" scenario.

Along with the proprietary GIS software like ArcGIS from ESRI, Open Source tools nowadays are of great importance in the geoinformation research. A review of Open Source QGIS forestry plugins done in the study conducted by Podolskaia (2021c) described plugins for the tasks of forest fire and forest resources monitoring and management. Plugin analysis done in this work was aimed to help future researchers by providing them with a list of QGIS plugins compatible to QGIS version 3.18 (as an example of version available for the users in 2021) for a forestry GIS project. An option for future research subjects may be a development of plugins with available data in the form of cartographic services for territories of different spatial coverage, taking into account that archived data and their accessibility is a key asset in the forestry. Subject-related forest scope in the present-day repository of QGIS plugins tends to be relatively limited. Such review of plugin functionality has to be performed repeatedly, following the QGIS developments and trends. Overall,

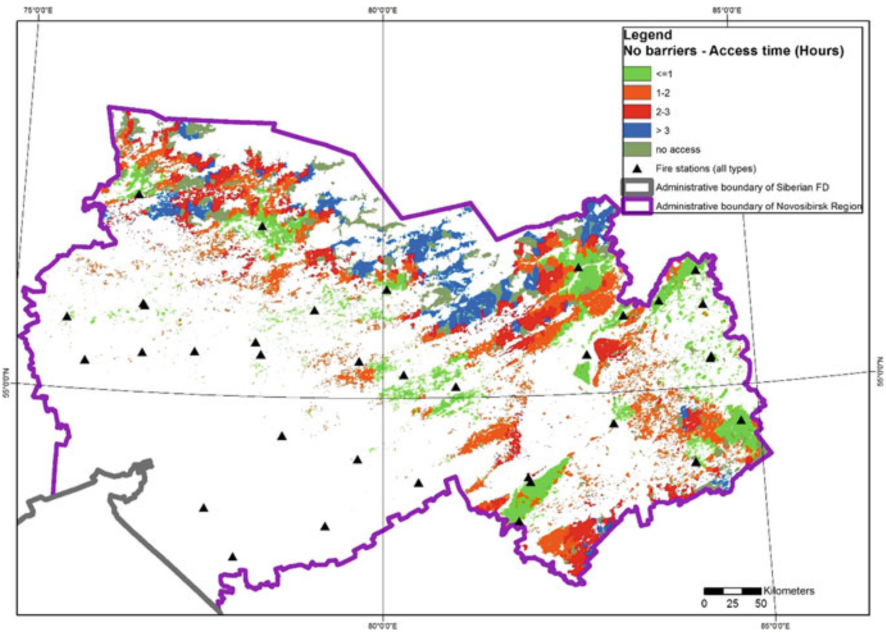

Fig. 6 Transport accessibility of forest resources in Novosibirsk Region. No-Barriers scenario classified by time, in hours (Podolskaia et al. 2020c)

the role of Open Geodata and Open Source GIS instruments will be stably very important in the forestry industrial and scientific projects.

4 Forest Roads as Effective Infrastructures for Fire Protection

Forest fire is recognized as one of the most detrimental natural disasters damaging forest resources. Aricak et al. (2014) facilitated high-resolution GeoEye satellite images and GIS data to investigate the potential fire risk zones in the forest area based on stand characteristics (age, crown closure, tree species). The flowchart of the implemented methodology is given in Fig. 7. In the study, the road networks in the forest area located in the Central District of the Kastamonu Regional Forest Directorate in Turkey were also included in the database. The fire trucks used during extinguishing of forest fires were able to spray water and chemicals with the pressure of 40 bars. Thus, in spite of ground slope steepness, a fire truck can intervene in an area with a minimum diameter of 400 m. Then, a buffer zone with the width of 400 m was generated for both sides of the roads using proximity tool in ArcGIS. Finally, the areas that can and cannot be intervened in the potential fire risk areas from the existing roads have been effectively determined by using GIS techniques. In a similar study conducted by Drosos et al. (2014), a model was developed to optimize opening ups in forest lands by primarily considering the fire prevention and

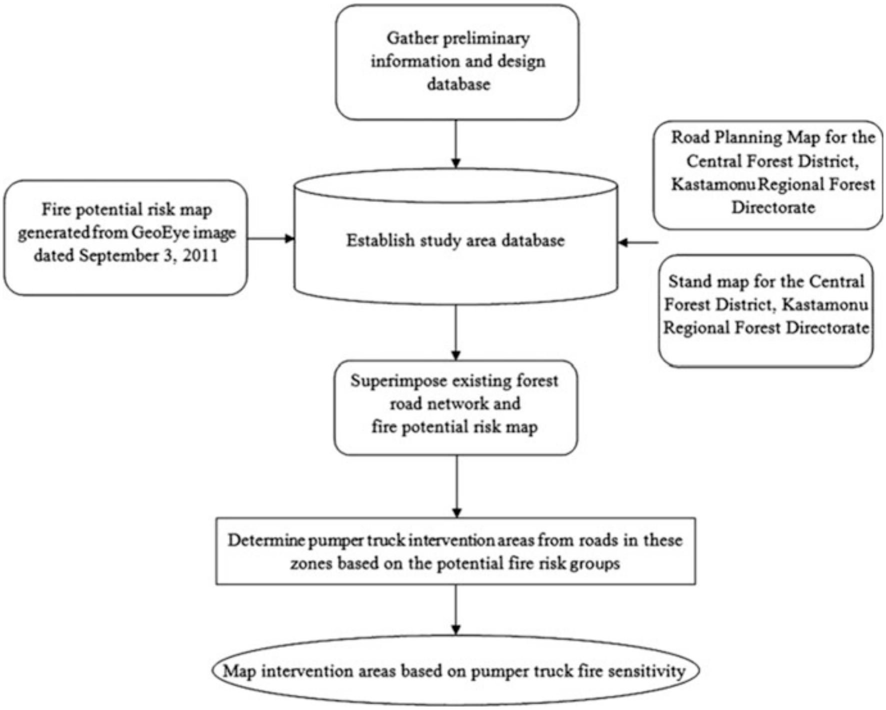

Fig. 7 Work flow of the study (Aricak et al. 2014)

suppression. The fire-suppression buffer zones were generated based on topography to define the lands being reached by the hoses of fire trucks. In the study, the buffer widths were considered as 150–300 m for uphill and 250–500 m for downhill from a location where the fire trucks are located.

Akay et al. (2017) searched for the fire-access zones by fire trucks in forested areas located in Kahramanmaraş where forests are sensitive to forest fires because of high temperatures and low humidity in summer season. In the study, GIS techniques were used to determine fire-access zones in forested areas by using the reach distance of the water sprayed by the fire hoses of fire trucks. The accessible buffer zones were defined from both sides of the roads, while taking into account ground slope, terrain structures (uphill, downhill, and flat), and the capabilities of the fire trucks. In the first stage, GIS database was generated to produce necessary data layers including road network map, forest land map, and fire sensitivity map. The ground slope map was produced using the Digital Elevation Model (DEM) derived from an ASTER satellite image. Then, the terrain structure of the study area was produced by considering the road network as the reference surface. For the locations over the reference surface, the terrain structure was determined as uphill, while it was downhill when they are under the reference surface. The locations that were at the same elevation with the reference surface were defined as flat areas. In the study,

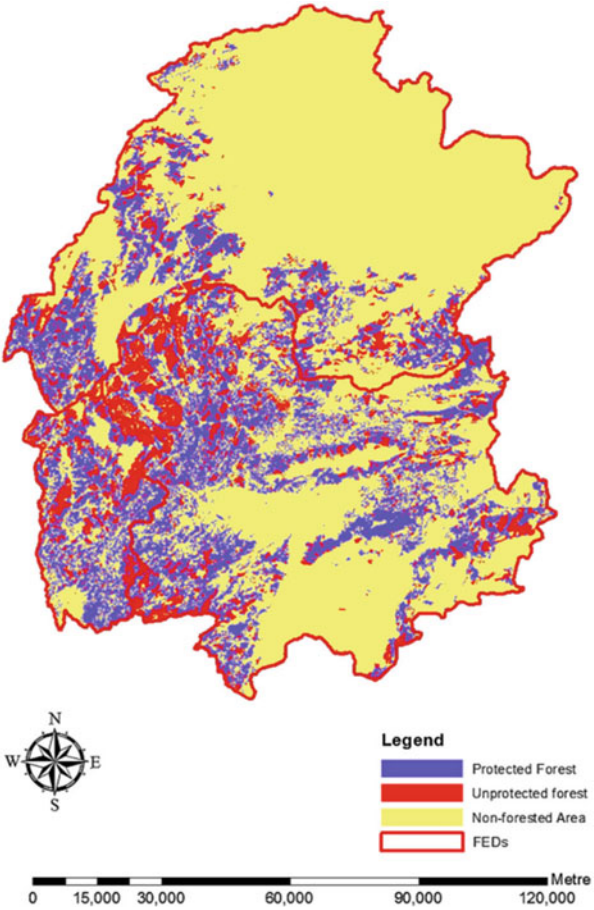

Fig. 8 The accessible and inaccessible forest areas

specific formulas were developed to determine the fire-access zone widths for downhill, uphill, and flat areas, considering the maximum water pressure at the pump, the minimum water pressure at the nozzle, the water pressure loss for each 10 m distance from the fire truck due to friction, and the ground slope. The areas with very high slope (more than 60%) were excluded from the fire-access zones since it could be unsafe and not applicable to conduct firefighting on steep slopes. Finally, the fire-access zone map was generated, indicating protected and unprotected forest areas (Fig. 8). The results indicated that the accessible forests, sensitive to fire with the first, second, and third degrees, were 69.59%, 69.96%, and 67.16%, respectively. The results revealed that determining the areas outside of reach distance of the hoses can provide an important information to evaluate the capabilities of the road network in firefighting activities.

Forest road networks are the most important infrastructures that provide access to forest areas for the protection and operation of forest resources. Increasing vehicle speed by improving road standards, especially in forests with high fire risk, will make a significant contribution to the expansion of accessible forest areas within the critical response time. Therefore, the improvement of road standards and the effectiveness of firefighting activities should be evaluated together. Akay et al. (2021) used GIS techniques to search for the potential contribution of improving road standards on expanding the forest areas that can be reached by the ground team within the critical response time. The study was implemented in the first-degree fire-sensitive forests located in Mediterranean city of Kahramanmaraş in Turkey. In the study, primarily the forest areas that can be reached by the firefighting team (six available teams in the region) within the critical response time were determined by considering the existing road network in the study area. Then, the possible increase in the accessible forest areas with high fire risk was investigated considering the improved road standards with higher vehicle speed on forest roads. In the solution process, the new service area method of Network Analyst tool in ArcGIS was used to determine the forest areas that firefighting team can reach within the critical response time. The results indicated that the accessible forested areas in critical response time increased by 19% by considering improved road standards (Fig. 9). They emphasized that increasing the design speed of the forest roads minimizes the arrival time of ground teams to the fire, which increases the accessible forest areas in critical response time.

In a study conducted in Tirana Albania, Haska et al. (2021) generated digital data layers for the locations of fire stations and road networks using ArcGIS 10.4 software. They determined the forest areas that firefighters could reach within the critical response time to the fire using Network Analyst. According to result of the study, it was found that 27% of the forest areas in the study area at Tiran was accessed by the ground team within the critical response time. In the application, an optimal location was suggested for the additional station which potentially increased the accessible forest areas up to 65%. In a similar study, Laschi et al. (2019) emphasized the essential rules for planning efficient forest road network in fire-sensitive forest lands. They suggested that the functions of forest roads should be analyzed in fire prevention and suppression and the importance of forest roads for protecting forests against fires should be considered in planning and building stages. Besides, the construction and maintenance characteristics should be considered for building and maintaining an efficient forest road network against fires. As a concluding remark, it was emphasized that road maintenance activities should be performed appropriately to have efficient transportation accessibility to potential forest fire areas.

5 Conclusion

This chapter described three topical directions of international research in the forestry spatial modeling indicating the optimality of access routes to forest fires and accessibility of forest resources and forest fires and highlighting the forest roads as a key element of forestry infrastructure. Ground transport features are regularly changing geometrically and attributively and becoming just more complex from

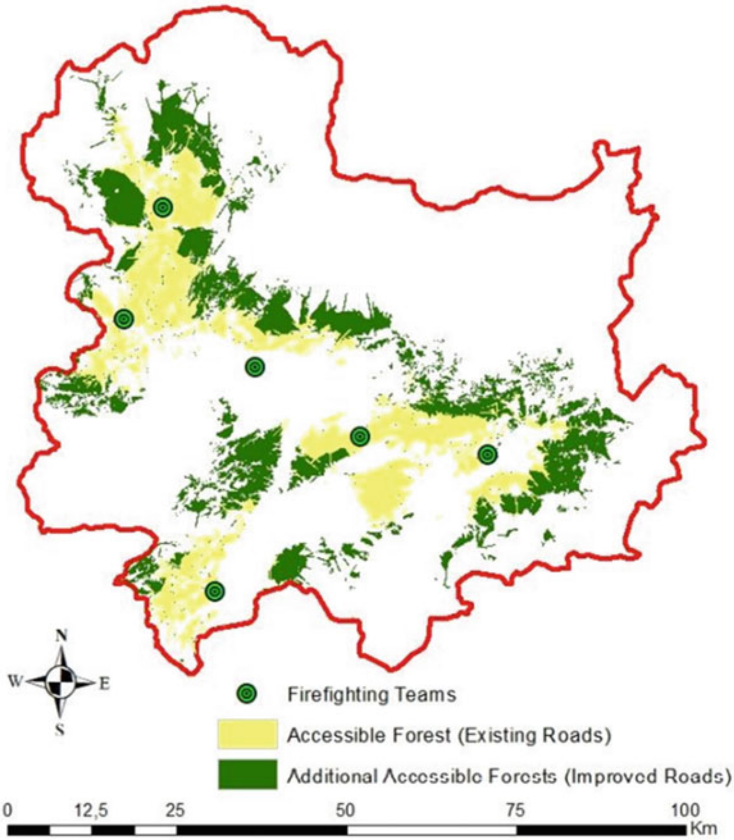

Fig. 9 The accessible forest areas for existing roads and improved roads

their technical maintenance, data management, and data analysis points of view. Forestry as industry uses a mixed network consisting of public off-seasonal and seasonal roads as well as of special forest roads used for logging purposes mainly.

Experience of two countries with different geographical location, state forestry situation, rules in the forest management, as well as spatial extents of key areas gave an opportunity to find the commonalities and differences in the undertaken studies. For example, research done by Turkish scientists confirmed by calculations that improved road standards and timely and appropriate maintenance of forest roads would improve the accessibility to the forest resources and forest fires.

The presented examples also show that current and future research directions are undoubtedly based on the combination of network analysis, decision support systems, and forest management scenarios with the help of modern GIS, namely, extensions and plug-ins of proprietary and Open Source software. Supporting cartographic materials with research key areas included in the chapter served as spatial modeling results' visualization.

Authors' Contributions All authors performed the same effort in this study. They all wrote, read, reviewed, and decided to submit a chapter of a book.

Conflict of Interest No conflict of interest.

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