



# Effects of forest roads and an assessment of their disturbance of the natural environment based on GIS spatial multi-criteria analysis: case study of the University Forest of Taxiarchis, Chalkidiki, Greece

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## Abstract

The forest road network contributes to all aspects of the management and protection of natural ecosystems, such as fire protection and access to settlements, infrastructure and forest recreation. This has led to a constant demand for new roads and increased road density in forest areas. However, due to the environmental impact of such roads, a tool that takes into account all the parameters that they affect and evaluates the spatial distribution of forest-road-induced disturbance is needed. The present research highlights a multi-criteria evaluation (MCE), based on a spatial approach that utilizes geographical information systems (GIS), for estimating both the impact of the forest road network and the absorptiveness of the natural environment for that impact. The University Forest of Taxiarchis, Greece, was selected as it combines both timber production and recreation characteristics. Primary data were collected through the management plan for the area and the road network was categorized. A variety of factors regarding forestry, wood extraction methods and production, and social and topographical criteria were examined and scored based on their weighting factors. The results regarding the impact and the absorptiveness were analyzed in order to assess the spatial disturbance. The analysis showed that the spatial environmental impact of the forest roads is crucial and that MCE methods should be applied in environmental impact assessment (EIA) in order to support decision-making systems (DMS) for new road construction and to enhance environmental integration.

**Keywords** Multi-criteria evaluation · Forest roads · Spatial optimization · Environmental assessment

## Introduction

A forest road is a type of permanent technical infrastructure found in forests and forested areas that covers all aspects of the multi-functionality that forest ecosystems serve. It supports timber production and the harvesting of forest and

non-forest products and it enables access to recreational areas. Above all, it is the main protection factor, especially when dealing with forest fires, as the suppression (Akay et al. 2012) of forest fires is achieved to a large extent by ground-based motorized means (Thompson et al. 2021). In addition, forest roads are crucial for mountain settlements, which rely on forest ecosystems for their development and daily life (Arabatzis et al. 2010). All these factors constantly lead to the need to create new forest roads, something that often conflicts with the restrictions set for forest conservation (Stergiadou et al. 2006).

Forest ecosystems provide a wide range of environmental, economic and social services to human societies (Winkel et al. 2022; Tadesse et al. 2022). They contribute to limiting and dealing with climate change (Andrea 2022), they provide the production of wood and forest products (Sen Wang 2013), and they promote recreation and improvements in human welfare and quality of life (Badea and Apostol 2020). This multi-functionality of forest ecosystems has highlighted the need for their protection and conservation, and the need

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for sustainable management of forest lands has been shown (Augustynczyk et al. 2020; Thomas et al. 2022; Basknet and Keles 2005). In recent decades, there has been an awareness regarding the impact of human intervention—in particular, human constructions and infrastructure—within forest areas (Baraloto et al. 2015; Escobedo et al. 2019; Kazama et al. 2021; Reddiar and Osti 2022; Mohammed et al. 2022). Contemporary policies and strategies for the conservation and protection of forests determine, in particular, the types and sizes of technical projects that are allowed to be implemented within forest ecosystems (Maier et al. 2021).

A successful forest road network is considered to be one that has the optimal density and spatial variability to serve all the parameters that concern both the protection of the natural environment and servicing human activities (Stückelberger et al. 2006a; Tampekis et al. 2015). To achieve sustainable management, forest stakeholders are called upon to balance the environmental, economic and social costs and benefits when planning the forest road network (Pelyukh et al. 2021; Stückelberger et al. 2007) by having a complete view of the resulting spatial disturbance (Akay et al. 2020). The forest road network and forest accessibility should provide access for fire prevention, should support logging activities (Gomes et al. 2021) and recreation, and should connect mountain settlements (Kantartzis et al. 2021). On the other hand, it should not alter the natural landscape (Jones et al. 2000; Trombulak and Frissell 2000); should not disturb the fauna, the wildlife (Boston 2016) and in general the biodiversity (Saraswati et al. 2019); and the construction and maintenance operations that are implemented should not be costly (Kerameti et al. 2020).

This necessity to balance the socio-economic benefits with the environmental cost of the disturbance caused by forest roads has led many researchers to develop methods which examine the environmental impact of forest roads in order to achieve sustainable management (Aguir et al. 2021; Dangerfield et al. 2021; Jung et al. 2013; Tampekis et al. 2018; Yildirim and Kadi 2020; Olander et al. 1998; Sekulic et al. 2021). An integrated approach to the environmental impact of forest roads is also important for developing decision support systems (DSSs) for the construction of new forest roads (Jaafari et al. 2015). The optimization of the spatial distribution of the forest road network leads to the minimization of its environmental impact (Stergiadou et al. 2003) and at the same time promotes its other functions (Silva et al. 2020; Bapapour et al. 2018). According to Stückelberger (2006b), the development of an optimum forest road network relies on three main factors: the life cycle cost, the ecological effects, and finally the natural environment attractiveness.

Until recent decades, the planning and the distribution of the forest road network was dependent on the logging and skidding costs (Aruga et al. 2005; Liu and Sessions 1993; Afify et al. 2023). Environmental awareness and

contemporary environmental approaches (Tello et al. 2022) have led to the development of multi-criteria methods for assessing the spatial disturbance caused by a forest road network, which take into account forestry, topographical and socio-economic factors (Kantartzis and Malesios 2018; Caliskan 2013; García-Rodríguez et al. 2021; Jusoff 2008; Stergiadou and Eskioglou 2006). A methodology that combines the cost and environmental factors (Schönauer et al. 2019) has been developed using the Delphi method and sensitivity analysis (Hayati et al. 2013a, b).

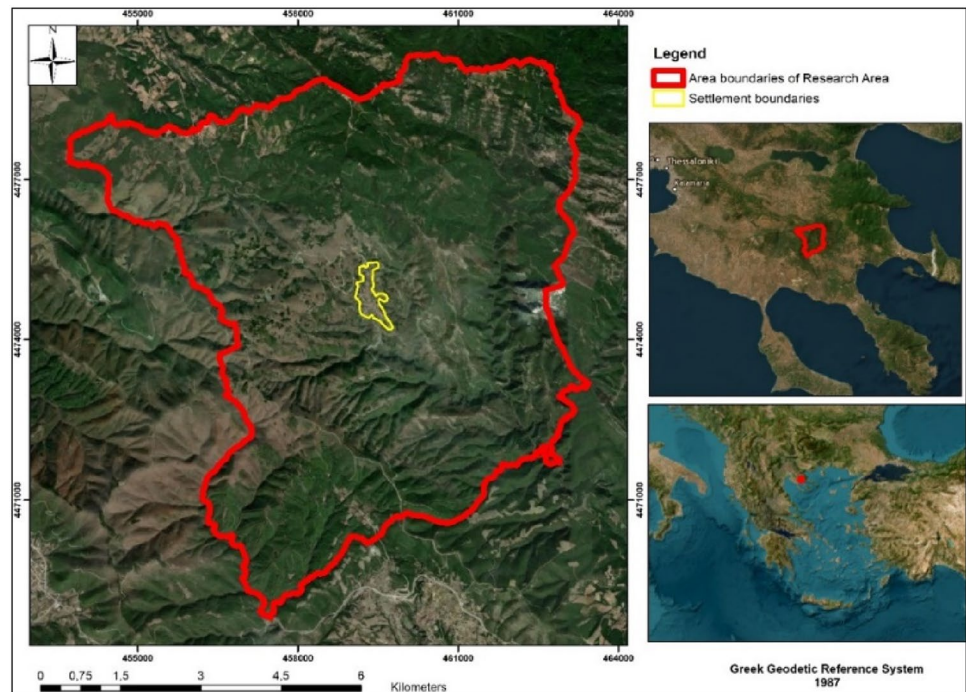
This research aims to present a multi-criteria analysis method based on geographic information systems (GIS) for the assessment of the spatial variability of the forest road network and its impact on the natural environment. The combination of an MCE method with GIS is a strong tool for supporting decision analysis systems (Shuaibu and Kara 2019; Papamichael et al. 2023a, b). The method takes into consideration two general categories of criteria: the evaluation of the intensity of the impact of the forest roads and the evaluation of the absorption of the impact of the forest road by the natural environment (Picchio et al. 2018; Zhang et al. 2020; Tampekis et al. 2015; Acar et al. 2017). This approach makes it possible to assess the spatial distribution and the management of the forest road network in combination with the ability of the natural environment to absorb the impact. The proposed method fits within the framework of the United Nations Sustainable Goal 12 (sustainable consumption and production)—particularly target 12.7, which promotes public procurement practices which are considered sustainable, in accordance with national policies and priorities.

## Materials and methodology

### Research area

To implement the research, the forest complex of Taxiarchis (Chalkidiki, Greece) was selected. The size of this area is approximately 5870.5 ha. In 1934, it was granted by the Greek state to Aristotle University of Thessaloniki for the purposes of education, research and the establishment of a contemporary model forestry. The ownership of the area by the university has led to the availability of a variety of scientific data for this area, which are used for the development of research programs. In Fig. 1, the location of the area in the wider southeastern Mediterranean is presented. It is located on the southwest side of Mount Cholomontas between latitudes 40° 23' N and 40° 28' N and longitudes 23° 28' E and 23° 34' E. The management of the area belongs to Aristotle University's Forest Administration and Management Fund, which is responsible for the logging program and all of the work that takes place in

**Fig. 1** Location map of the research area



it. The administration of the area belongs to the Municipality of Polygyros, R.D. of Central Macedonia.

Within the area is the homonymous settlement of Taxiarchis, which, according to the 2011 census, has a population of 1070 residents. In addition, the university maintains accommodation facilities for students and staff. Finally, a variety of small hotels and restaurants are also located in the area. A total of 27.17 ha, which corresponds to 46.29% of the total area, are considered as protected areas and are included in the European Natura 2000 network (site codes GR1270001 and GR1270012). The vegetation zones, which are found within the area, according to the Greek classification system are the *Quercetalia ilicis* and the *Quercetalia pupescens* (Gatzogiannis et al. 2013; Spanos et al. 2018). More than 36 dominant native forest species appear, while at the same time 17 forest species that were artificially established after reforestation can be distinguished.

Mediterranean forest ecosystems are distinguished by special characteristics, among which are increased biodiversity and intense variations of the relief. The main reasons for choosing the specific area to implement the present research were that it is a representative example of Mediterranean ecosystems and, due to the variations of the relief, it shows a great biodiversity in terms of flora and fauna. In addition, it is both a productive forest, with organized logging, and a recreational forest.

## Data collection

The majority of the data used for the evaluation of the criteria and the implementation of multi-criteria analysis came from the Forest Management Plan of the University Forest of Taxiarchis, Chalkidiki, Greece, for the period 2012–2021. The plan includes all the necessary information about the percentage of timber produced and the logging procedures. It also contains a detailed inventory of the ecological conditions of the area. Another important parameter for the implementation of the research was the availability in digital geospatial form of the forest road network. According to Greek legislation, forest roads are classified into four categories (A, B, C and tractor roads), as presented in Table 1. Using orthophotos from the Hellenic Land Registry, the entire road network of the area was digitized and classified into the mentioned categories. This task was carried out through a detailed analysis of the geometric elements of the roads. In addition, geometric elements of the forest road network were extracted from forest service records and previous surveys (Stergiadis 1977).

The method includes the analysis of criteria related to the topography of the area. For this purpose and to develop the analysis using geographical information systems, a digital elevation model (DEM) was used. The raster DEM of the area with a cell size of  $4 \times 4$  was obtained from the Greek Land Registry.

**Table 1** Technical specifications for the categorization of forest roads according to Greek legislation

Technical specifications	Categories of forest roads			Harvesting routes Skidding roads
	A	B	C	
<b>Deck width</b>				
Earthy and semi-rocky soil	6–8 m	4–6 m	4–5 m	2.5–3 m
Rocky soil	6 m	4 m	5 m	2.5 m
<b>Minimum radius of curve</b> $R_{min}$				
On the curves	30 m	25 m	20 m	10 m
On meanders	20 m	20 m	15 m	10 m
<b>Longitudinal slope <math>S_{max}</math></b>				
Downhill	8%	8%	12%	25%
Uphill	6%	6%	–	–
<b>Technical constructions</b>				
Drainage ditches	Yes	Yes	Yes	No
Technical works	Yes	Yes	Yes	No
Formation of slopes	Yes	Yes	Yes	No

### Implementation of multi-criteria analysis

For the implementation of the MCE method, a variety of criteria were taken into consideration. Following Stergiadou (2006), Tampekis et al. (2015) and Zhang et al. (2020), the method includes two major categories of criteria. The first category includes the criteria for the assessment of

the intensity of the impact of both the forest road network and the wood production on the natural environment. The second category includes the criteria for evaluating the absorptiveness of the natural environment for the environmental impact. In Fig. 2, the criteria from each category are presented.

Each criterion is graded within the MCE, with 100% representing an excellent score. The impact of each criterion acts to reduce the score. In addition, each of the criteria has a weighting factor of 1, 2 or 3.

### Criteria for the assessment of the intensity of the impact of forest roads on the natural environment

A. The forest road network density and the percentage of protected area (weighting factor: 3)

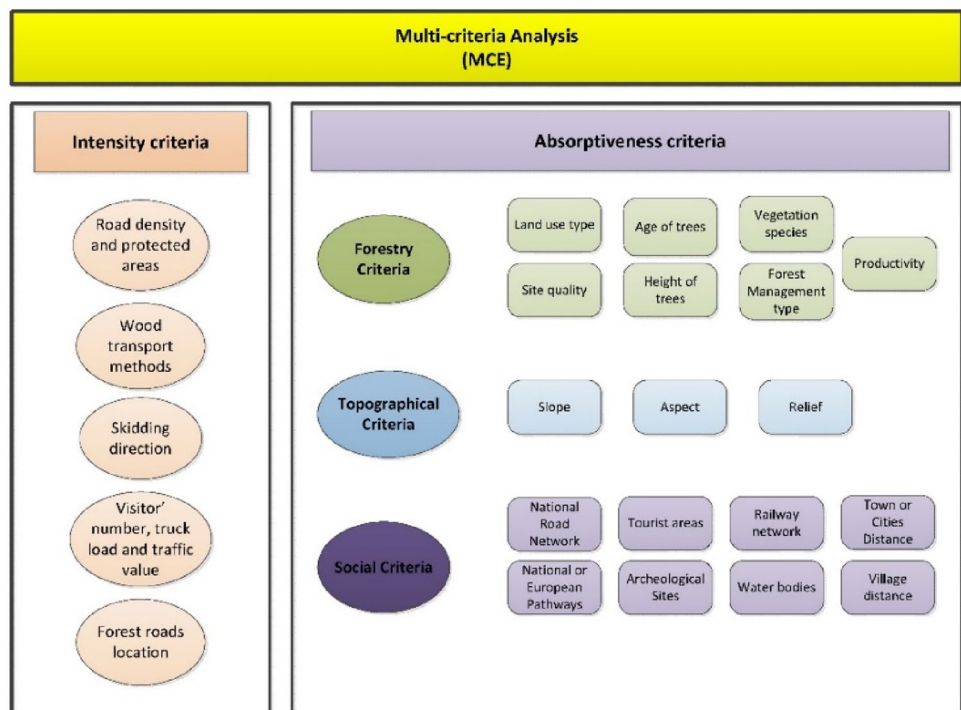
The density of the forest road network is calculated according to the equation

$$D = \frac{\sum L}{A},$$

where  $D$  is the forest road network density (m/ha),  $L$  is the length of the forest road network (m) and  $A$  is the size of the area (ha).

The analysis performed to calculate this criterion was implemented in ArcGIS software. The total length of the forest road network per road category was calculated and

**Fig. 2** Presentation of the multi-criteria analysis structure



divided by the total size of the area. For the percentage of protected area, the Buffer tool was implemented for an area of 200 m, which, according to the Greek Fire Service, is the immediate fire protection area along the forest roads. This criterion is scored by decreasing the score from 100 (corresponding to excellent) according to how much  $D$  exceeds 12.5 m/ha and how much it exceeds 15 m/ha, as well as how much lower than 85% the percentage of protected area is.

## 2 Wood transport methods (weighting factor: 2)

The total percentage of the logging timber that is not transported with a rope crane or draft animals is scored as a reduction from an excellent score of 100. The information needed for evaluating this criterion was derived from the logging tables of the management plan.

## 3 Skidding direction (weighting factor: 1)

The percentage of skidding which is not done diagonally ( $45^\circ$ ) or parallel to the forest road is graded as a reduction from the optimum score of 100. The information for the evaluation of the criterion was derived from the forest cooperative of the area.

## 4 Number of visitors (visitor capacity of the area; weighting factor: 2)

The amount by which the number of visitors exceeds the visitor capacity of the area, evaluated as a percentage of the visitor capacity, is scored as a reduction from the optimum score of 100.

## 5 Traffic load and traffic value (weighting factor: 2)

The number of vehicles and the percentage of them which have more wheels than permitted by the road specification are also scored as a reduction from an excellent score of 100. The information needed for the evaluation of this criterion was derived from the municipality authorities and the local forest cooperative.

## 6 Locations of the forest roads (weighting factor: 3)

This criterion accounts for the distances of the forest roads from elements of the ecosystem. It is divided into three sub-criteria. The first is the distance from streams, the second is the road network outside the forest boundaries, and the third is the geological type of the ground on which the forest roads are established.

The percentage of roads that are located at a distance of less than 20 m from a stream is scored as a reduction from the optimum score of 100. For the calculation of this criterion, the

forest road network was combined with a hydrological map of the area. Then the Buffer tool was executed in the streams for an area of 20 m, and the Clip tool was implemented in order to retrieve the roads within the 20 m distance.

The percentage of forest roads which are less than 10 m outside the forest boundaries is also a reduction factor from the optimum score of 100. Finally, the percentage of forest roads which are constructed on unstable soils is scored as a reduction from 100. To obtain geological information on the area, data from the Greek Institute of Geological and Mining Research were analyzed.

## Criteria for the assessment of the absorptiveness of the natural environment

The criteria for the assessment of the absorptiveness of the natural environment for the impact of the forest road network are separated into three major categories: forestry criteria, topographical criteria and social criteria.

The forestry criteria have weighting factors of 3 and are as follows:

1. *The land use.* The percentage of the absorptiveness of the Forest is graded with the optimum score of 100, while the Forest Areas are graded with scores between 25 and 50, and the Barren Areas are given scores of 15. According to Greek legislation, areas where the canopy of forest species cover at least 30% of the land are characterized as Forest. Areas where the forest species canopy is between 5% and 25% are characterized as Forest Areas. The areas where the forest species canopy is less than 5% are characterized as Grasslands or Barren areas. For the calculation of this criterion, land use data from the European Union's program Corine 2018 were used.
2. *The site quality.* According to the forest management specification, all the areas are categorized into six classes depending on the site quality (I, II, III, IV, V, or VI), with the first class being the best and the sixth the worst quality. Thus, the first and second classes are scored as 100, the third and the fourth are scored as 50, and the fifth and sixth classes of site quality are scored as 25.
3. *The age of the trees.* When the forest clusters are group selective (there is no representation of all ages of forest trees), this criterion is graded as 100, when it is a gardening forest (there is a representation of all stages of forest trees growth and in a uniform way in terms of area) it is scored as 75, and when it is a same-age forest it is graded as 50.
4. *The height of the trees.* When the tree height is over 20 m, this criterion is scored as 100. When the tree height is between 10 and 20 m, it is scored as 75, and finally, when the tree height is less than 10 m, the criterion is scored between 25 and 50.

5. *The vegetation species.* When the forest consists of mixed forest species, this criterion is scored as 100. When it consists of broad-leaved trees, it is scored as 75, and when it consists of conifers, it is graded 65.
6. *The forest management type.* The spermatophyte type of management is graded 100. The coppice management type is graded 50. Finally, when the forest management is mixed type, the criterion is graded between 75 and 100.
7. *The forest productivity.* This criterion refers to the amount of timber harvested. For over 3 m<sup>3</sup> of logging per year, the forest corresponds to category I, and the criterion is scored as 100. For a logging volume of between 1 and 3 m<sup>3</sup> per year, the forest productivity corresponds to category II, and the criterion is graded 50. Finally, for productivity of less than 1 m<sup>3</sup> per year, the forest corresponds to category III, and the criterion is scored as 25.

The data for the calculation of forestry criteria 2–7 were derived from the Forest Management Plan.

The topographical criteria have weighting factors of 2 and are as follows:

1. *The terrain slope.* When the slopes are gentle (less than 8%), the criterion is scored as 100. When the slopes are medium (between 8 and 20%), the criterion is scored as 50, and when the slopes are steep (more than 20%), the criterion is scored between 25 and 5.
2. *The terrain aspect.* The scoring of this criterion depends on whether the area has a higher or lower altitude than 1000 m. Table 2 shows the level of absorptiveness based on the terrain aspect.
3. *The relief of the terrain.* For mild relief, the criterion is scored as 100. For intense relief, the criterion is scored as 15, and when the relief is mixed the criterion is scored as 50.

For the calculation of the above criteria, the Spatial Analyst Toolbox of ArcGIS was used—in particular, the

**Table 2** Grading of the terrain aspect criterion

Altitude	Aspect	Level of absorptiveness
<1000 m	Northerly	100
	East–west	75
	Southerly	50
>1000 m	Northerly	70
	East–west	100
	Southerly	70

Slope and Aspect tools—using the digital elevation model of the area.

The social criteria have weighting factors of 1, and they are: (a) the distance from the tourist destination, (b) the distance from the national road network, (c) the distance from the railway, (d) the distance from archaeological sites and places, (e) the distance from settlements and villages (with a population of less than 1000 citizens), (f) the distance from towns or cities (with a population of more than 1000 citizens), (g) the presence of a national or European path in the area, and finally (h) the distance from lakes and rivers.

The above indicators are scored according to the distance from the item of interest, as this reflects the impact. So, if the distance is between 0 and 1 km, the criteria are scored as 0; if the distance is between 1 and 2 km, they are scored as 10; if the distance is between 2 and 3 km, they are scored as 20, and so on. If the distance exceeds 10 km, the criteria are graded as excellent (a score of 100). Only the national and European path criterion differs from this, which is reduced from the excellent 100, whenever a road intersects a national or European path.

### Final grading by the MCE

Regarding the final grading by the MCE, the evaluation of the intensity of the impact of the forest roads (EI), and the evaluation of the absorptiveness (EA), the score of each criterion is multiplied by its weighting factor, and the total sum is divided by the sum of the weighting factors. The following equations display the final grading procedure:

$$EI = \frac{\sum_1^i (EI_i \times WF_i)}{\sum_1^i WF_i}, EA = \frac{\sum_1^j (EA_j \times WF_j)}{\sum_1^j WF_j},$$

where EI is the final grade of the impact intensity assessment, EA is the final grade in the evaluation of absorptiveness,  $EI_i$  are the impact intensity criteria,  $EA_j$  are the absorptiveness criteria, and WF is the weighting factor.

The above values are evaluated as follows. When the intensity EI is greater than 50% and the absorptiveness EA is greater than 50%, the construction of new roads is acceptable. When EI is greater than 50% and EA is less than 50%, or the reverse, the construction of new roads is acceptable with limitations. Finally, when both EI and EA have values of less than 50, the construction of new roads is acceptable only if technical projects for the restoration of the environment take place. In addition, the product of both EI and EA is calculated in order to estimate the disturbance in total.

## Results

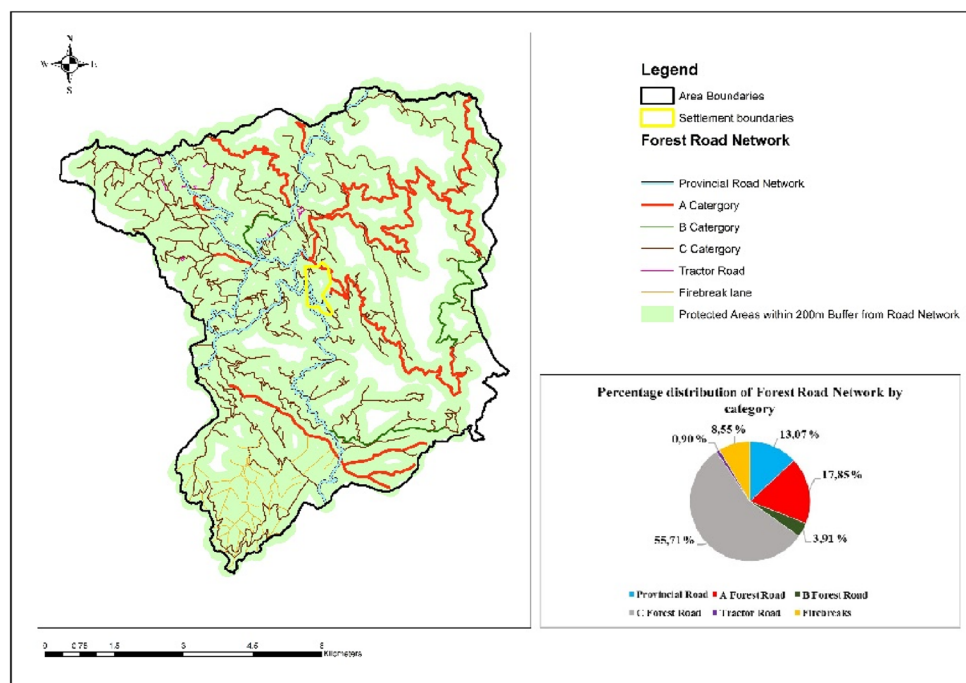
### Assessment of the intensity of the impact of forest roads on the natural environment

#### A. The forest road network density and the percentage of protected areas

The total length of forest roads in each category was calculated to be as follows: provincial roads 32,518 m, category A forest roads 44,425 m, category B forest roads 9730 m, category C forest roads 138,627 m, tractor roads 2228 m and firebreaks 21,285 m, which means that the total length of the forest road network is 248,813 m. Thus, the road density  $D$  for the area of 5870.5 ha is  $248,813/5870.5 \rightarrow D = 42.38$  m/ha. The total size of the protected areas was calculated to be 5352.92 ha, which indicates that 91.18% of the area is at a distance of 200 m from the nearest forest road, and protecting the forest from fire is possible using ground forces. Figure 3 shows both the road network and the protected areas in the research area.

The road density  $D = 42.38$  m/ha exceeds the value of 12.5 by  $42.38 - 12.5 = 29.88$  m/ha and the value of 15 by  $42.38 - 15 = 27.38$  m/ha. The percentages of exceedance are  $(100 \times 29.88)/42.38 = 70.51$  and  $(100 \times 27.38)/42.38 = 64.61$ , and their average is  $(70.51 + 64.61)/2 = 67.56$ . The percentage of protected areas exceeds 85%, so its does not lower the score for this criterion. Thus, the score for the criterion is  $100 - 67.56 = 32.44$  and the weighting factor is 3.

**Fig. 3** Forest road network in the research area: the categories of the roads and the protected areas within a distance of 200 m from roads are shown



#### 2 Wood transport methods

According to the Forestry Management Plan for the research area, a significant percentage of the transport of logging timber is done using tractors. Thus, this criterion is scored as 10 and the weighting factor is 2.

#### 3 Skidding direction

When the skidding is done with tractors, the direction is always diagonal or parallel to the forest road. Thus, the criterion is scored as 100 and the weighting factor is 1.

#### 4 Visitor numbers, traffic load and traffic value

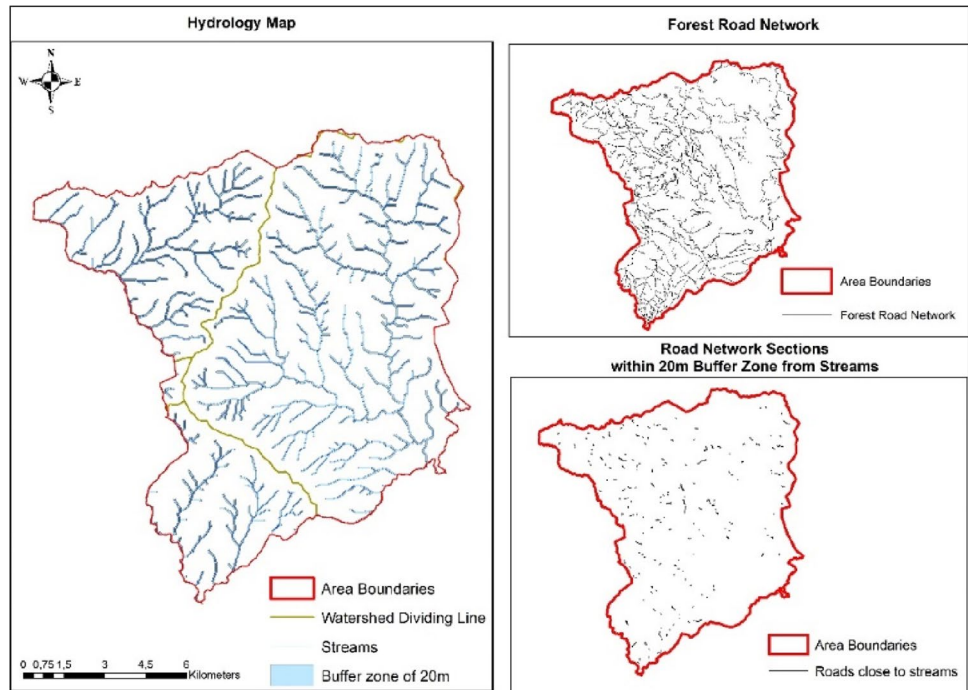
The research area is a place of recreation. According to the local authorities, the number of visitors does not exceed the capacity of the available infrastructure.

In addition, according to the local forest cooperative, there are no vehicles in the area which use wheels above the specification. Thus, the criterion was scored as an excellent value of 100 with a weighting factor of 2.

#### 5 Locations of the forest roads

The roads which are located within 20 m from streams are presented in Fig. 4. The total length was calculated to be 17,266 m, which represents a percentage of 6.94% in relation to the total length of the forest road network (248,813 m).

**Fig. 4** Road network within a distance of 20 m from streams

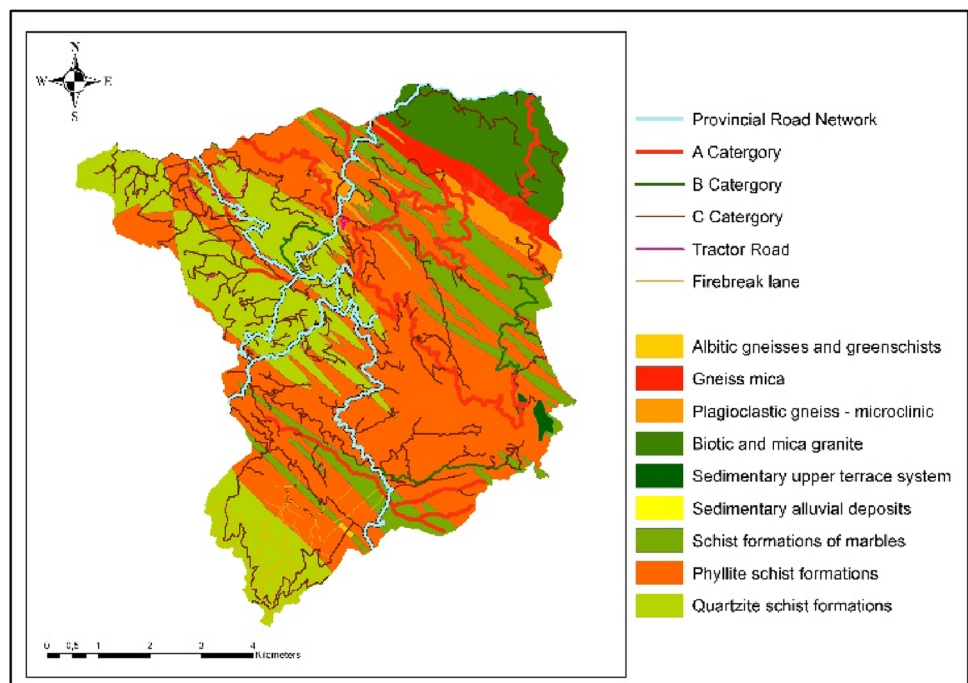


Thus, the criterion for the distance of streams was graded as  $100 - 6.94 = 93.06$ , with a weighting factor of 3.

In the study area, there are no roads which are located outside the forest boundaries. Thus, the criterion of distance from forest boundaries was scored as 100 and the weighting factor was 3.

According to a geological map of the area (Fig. 5), the forest roads do not pass through unstable soils. Thus, the criterion was scored as 100 and the weighting factor was 3.

**Fig. 5** Geological map of the research area





## Assessment of the absorptiveness of the natural environment for the impact of the forest roads

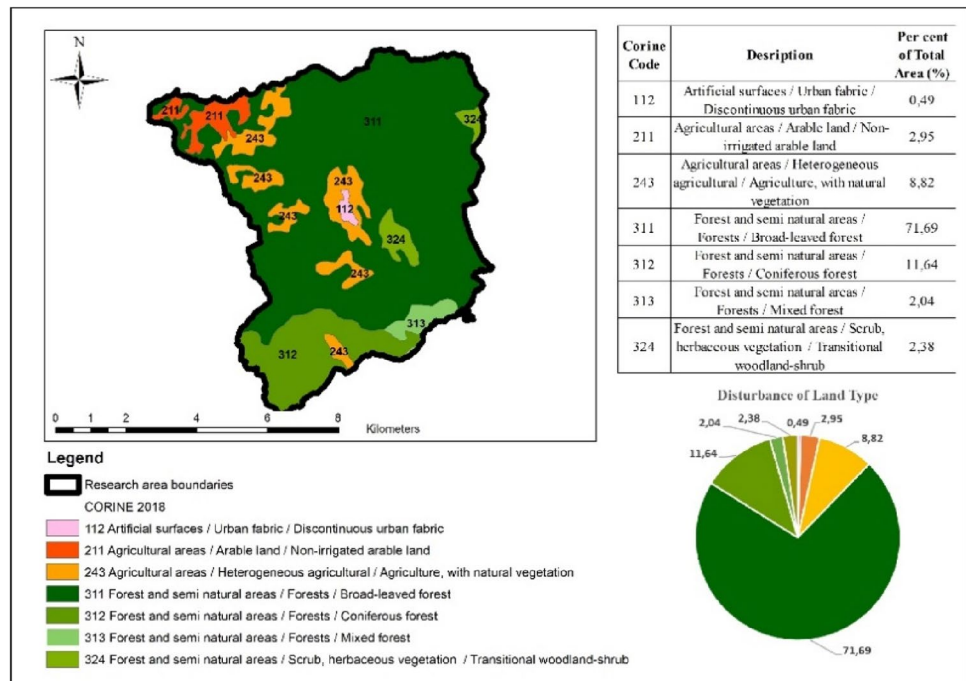
### Forestry criteria

Regarding the land uses of the area, Fig. 6 was created with data from Corine 2018. 85.31% of the area is forest (forest species canopy is over 30%), 2.38% is forest areas (forest species canopy is between 5% to 25%)

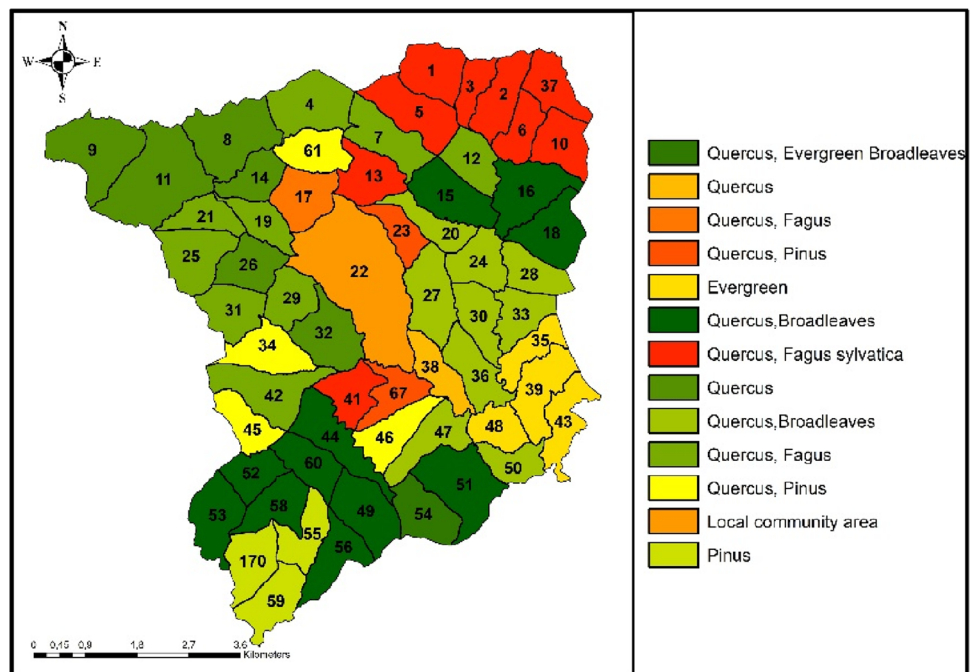
and the rest areas (farmland, artificial surfaces, shrubland and grassland) cover 12.31%. Thus, the criterion is graded as follows:  $0.8531 \times 100 + 0.0238 \times 75 + 0.1231 \times 15 = 88.94$ , with a weighting factor of 3.

According to the Forest Management Plan, the area is divided into 61 forest sections (Fig. 7). For each section, there is a detailed description sheet that includes its forestry parameters and predicted timber products. The description sheets are part of the Forest Management Plan and have

**Fig. 6** Land uses of the area according to Corine 2018 data



**Fig. 7** Forest sections in the study area according to the Forest Management Plan and presentation of the dominant forest species



detailed information about the management of each forest section.

For the site quality criterion, Fig. 8 displays, for each forest section, the percentage of each site quality category. 0.5% of the entire area has category I, 5.22% has category II, 32.87% has category III, 56.33% has category IV, and finally, 5.08% has category V site quality. Category VI does not exist in any forest section. The site quality criterion is graded as follows:  $(0.5\% + 5.22\%) \times 100 + (32.87\% + 56.33\%) \times 50 + 5.08\% \times 25 = 51.59$ , with a weighting factor of 3.

Among the 61 forest sections, 57 are characterized as same-age forest while the other four are characterized as almost the same age with decency for group selection harvesting. Thus, the age of trees criterion is graded as follows:  $(57/61) \times 50 + (4/61) \times 70 = 51.31$ , with a weighting factor of 3.

80% of the area has trees between 10 and 20 m high. The remaining percentage is divided equally between higher and lower trees. Thus, the height of trees criterion is graded as follows:  $0.80 \times 75 + 0.10 \times 100 + 0.10 \times 40 = 74$ , with a weighting factor of 3.

71.69% of the area has broad-leaved species, 11.64% has coniferous trees, 2.04% has mixed forest, 11.77% is agricultural land, 2.38% is transitional woodland (shrubs) and 0.49% is artificial land. Thus, the vegetation species criterion is graded as follows:  $71.69\% \times 75 + 11.64\% \times 65 + 2.04\% \times 100 = 63.37$ , with a weighting factor of 3.

The basic forest management type of the area is spermatophyte. In the past, there were a few clusters where clearcut logging was applied, which were managed with coppice management. However, the present management plan has

the complete reduction of the forest to a spermatophyte type as a goal. So, the forest management type criterion is scored as 100 and the weighting factor is 3.

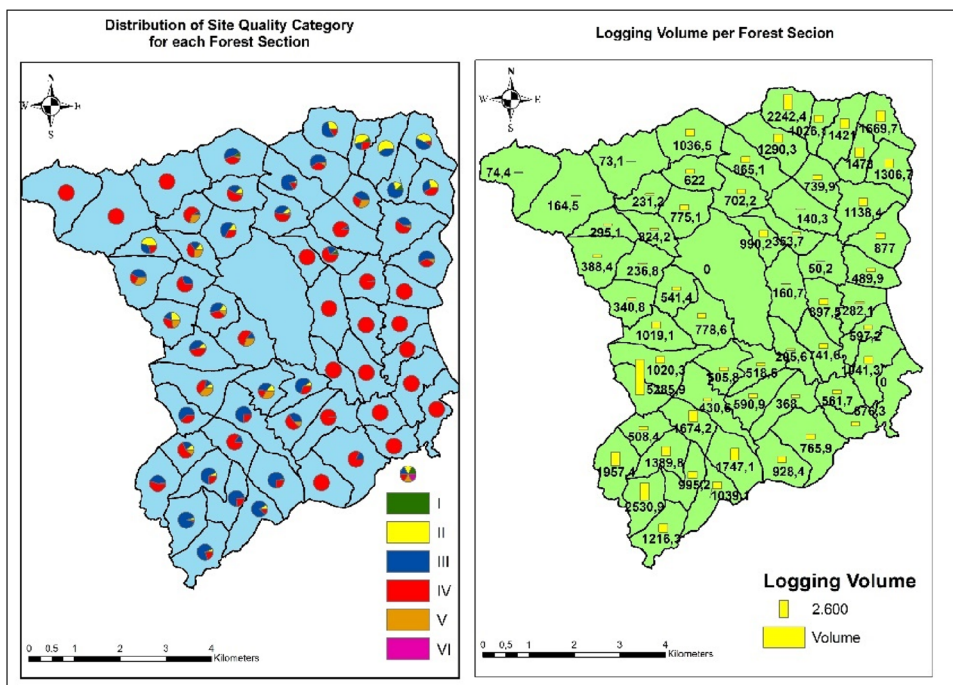
Regarding the productivity criterion, Fig. 8 shows the total volume of the available logging per forest section, according to the Forest Management Plan, for the 10-year period between 2012 and 2021. The cumulative total volume of timber to be cut for the mentioned period is equal to 52,214.1 m<sup>3</sup>. Section 22, as displayed in Figs. 7 and 8, does not have any logging volume because it consists of the Taxiarchis settlement and the buildings of the university and the forest authorities. Thus, the size of the area in which logging works take place equals 5509 ha. The annual logging volume of the area equals to  $52,214.1/10/5509 = 0.948$  m<sup>3</sup>/ha/year. So, the productivity criterion for category III is graded 25, with a weighting factor of 3.

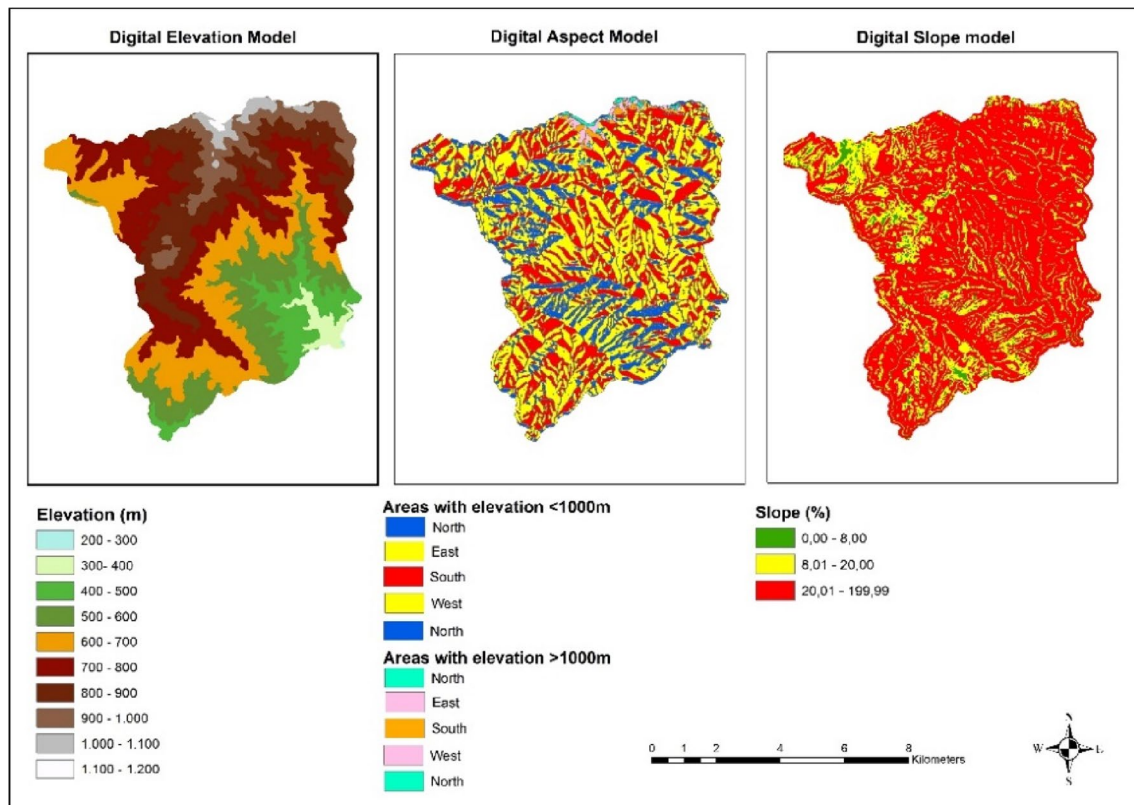
**Topographical criteria**

Figure 9 displays the analysis performed using the ArcGIS software to assess the topographical criteria. The digital elevation model (DEM) was imported, and the Aspect and Slope tools were executed. The rasters which were produced were reclassified in order to highlight areas to aid criteria scoring.

The DEM showed that the only 2.24% of the total area has an elevation of over 1000 m, while the rest (97.76%) has an elevation of less than 1000 m. For the area with an elevation of over 1000 m, the Aspect tool showed that 22.70% has a northerly aspect, 32.57% has a southerly aspect, and the rest (44.73%) has either an easterly or westerly aspect. For the

**Fig. 8** Assessment of the site quality and the productivity criterion





**Fig. 9** Assessment of the topographical criteria for absorptiveness of the natural environment

area with an elevation of less than 1000 m, the Aspect tool showed that 18.32% has a northerly aspect, 31.64% has a southerly aspect, and the rest (50.04%) of the area has either an easterly or a westerly aspect. Thus, the aspect criterion, which has a weighting factor of 2, is graded according to Table 2 as follows: aspect criterion =  $2.24/100 \times (22.70/100 \times 70 + 32.57/100 \times 70 + 44.73/100 \times 100) + 97.76/100 \times (18.32/100 \times 100 + 31.46/100 \times 50 + 50.04/100 \times 75) = 71.85$ .

For the slope criterion, the analysis showed that 5.73% of the area has gentle slopes of between 0 and 8%, 21.22% has medium slopes of between 8 and 20%, and the remaining 73.05% has steep slopes of over 20%. The steep slopes exceeded 60% for the greater part of the area. Thus, the slope criterion is graded  $5.73\% \times 100 + 21.22\% \times 50 + 73.05 \times 20 = 30.95$ , with a weighting factor of 2.

The relief of the terrain was mixed, so the criterion is scored as 50 with a weighting factor of 2.

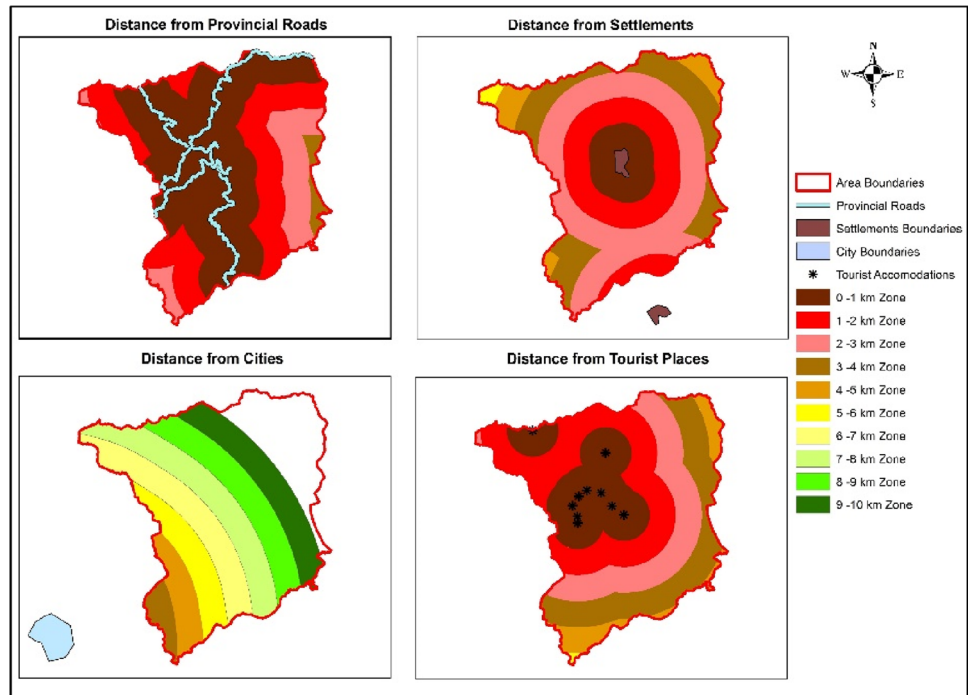
### Social criteria

Regarding the social criteria, the area is considered a tourist destination because there are tourist accommodation

and the students from the university visit the area during the summer period. There are roads with total length of 32.52 km within the area which belong to the provincial road network. The settlement of Taxiarchis (population: approximately 900 citizens) exists within the area boundaries, and the settlement of Vrastama (population: approximately 800 citizens) is located 2 km from them. The city of Polygyros (population: 6121 citizens according to the 2021 census) is located around 5 km from the area. Figure 10 was created to grade the above criteria (tourist area, national/provincial road, village distance, town or city). Buffer zones that display the distance from each item of infrastructure were created. The percent cover of each zone was estimated by implementing a proximity and overlay analysis in ArcGIS. Table 3 shows the score for each buffer zone, which was multiplied by the percentage of the area that the corresponding zone covers, and the total score for each criterion was then calculated.

There is no railway, archaeological site, national or European path, or major lake or river less than 10 km from the research area's boundaries. Thus, these criteria were scored as excellent (100). All the social criteria have weighting factors of 100.

**Fig. 10** Proximity analysis for the assessment of the social criteria



**Table 3** Grading the social criteria based on the use of buffer zones

Buffer zone	Zone score	Provincial roads		Settlements		Cities		Tourist destination	
		Area coverage	Score	Area coverage	Score	Area coverage	Score	Area coverage	Score
0–1 km	0	55.66%	0	11.31%	0	0%	0	23.66%	0
1–2 km	10	28.19%	2.82	24.28%	2.43	0%	0	29.02%	2.90
2–3 km	20	13.69%	2.74	36.69%	7.34	0%	0	20.32%	4.06
3–4 km	30	2.46%	0.74	21.06%	6.32	3.56%	1.07	20.61%	6.18
4–5 km	40	0%	0	5.70%	2.28	7.09%	2.84	6.15%	2.46
5–6 km	50	0%	0	0.96%	0.48	10.02%	5.01	0.24%	0.12
6–7 km	60	0%	0	0%	0	15.57%	9.34	0%	0
7–8 km	70	0%	0	0%	0	17.29%	12.10	0%	0
8–9 km	80	0%	0	0%	0	14.85%	11.88	0%	0
9–10 km	90	0%	0	0%	0	14.20%	12.78	0%	0
> 10 km	100	0%	0	0%	0	17.42%	17.42	0%	0
Total score		6.30		18.84		72.44		15.73	

**Final grading**

Table 4 presents the final score and the results from the implementation of multi-criteria analysis. The final grade from the assessment of the intensity of the impact of the forest roads, EI, was found to be 78.76%, while the absorptiveness of the forest road network from the natural environment, EA, was found to be 62.32%. Both results were greater than the limit of 50%, while their product equals  $78.76\% \times 62.32\% = 49.08\%$ , which is marginally less than 50%. Thus, the result of the MCE is that the forest road network in the research area has an acceptable environmental impact.

**Conclusions**

Both results were greater than the limit of 50%, while their product equals  $78.76\% \times 62.32\% = 49.08\%$ , which is marginally less than 50%. Thus, the result of the MCE is that the forest road network in the research area has an acceptable environmental impact. These results were derived from a variety of factors, including forestry, topographical and social criteria. Each factor had its own weighting factor.

The multi-functionality of forest roads means that there is constantly a need to create new ones for reasons of

**Table 4** Aggregate scoring and final grade of the multi-criteria analysis

Criterion	Score	Weighting factor	Total score
Assessment of the intensity of the impact of forest roads in the natural environment			
Forest road network density and the percentage of protected areas	32.44	3	97.32
Wood transport methods	10	2	20
Skidding direction	100	1	100
Number of visitors	100	2	200
Traffic load	100	2	200
Forest road location/distance from streams	93.06	3	279.18
Forest road location/forest boundaries	100	3	300
Forest road location/geological type	100	3	300
Total		19	1496.5
Final grading: $EI = \Sigma(EI \times WF) / \Sigma(WF) = 1496.5 / 19 = 78.76$			
Assessment of the absorptiveness of the the natural environment for the forest road impact			
Forestry criteria			
Land use	88.94	3	266.82
Site quality	51.59	3	154.77
Age of trees	51.31	3	153.93
Height of trees	74	3	222
Vegetation species	63.37	3	190.11
Forest management type	100	3	300
Productivity	25	3	75
Topographical criteria			
Slope	30.95	2	61.9
Aspect	71.85	2	143.7
Relief	50	2	100
Social criteria			
National/provincial road	6.30	1	6.3
Tourist areas	15.73	1	15.73
Railway network	100	1	100
Towns or cities	72.44	1	72.44
Villages/settlements	18.44	1	18.44
Pathways	100	1	100
Archeological sites	100	1	100
Water bodies	100	1	100
Total		35	2181.14
Final grading: $EA = \Sigma(EI \times WF) / \Sigma(WF) = 2181.14 / 35 = 62.32$			

protecting and improving the infrastructure. Researchers need a tool such as the multi-criteria method presented here to monitor the environmental impact of the forest road network and thereby enhance decision-making systems. The presented MCE has the important advantage of taking into account all aspects of the impact on the environment, and it can also determine the extent to which the environment under study can absorb this impact.

The present method can be applied to decision analysis systems. Greek and European legislation requires the preparation of a detailed environmental impact study before the construction of a technical project. The majority of technical constructions, such as wind turbines, are directly connected to the parallel construction of forest roads. The introduction of this method into similar studies would lead to an

innovative method of performing an overall assessment of the environment.

In the research area of the University Forest of Taxiarchis, Chalkidiki, and also in similar areas, future research could focus on the accessibility of the area to ground firefighting vehicles. If the protection of the areas from fire needs to be enhanced by building new roads, the MCE can be revised and contribute to their optimal spatial distribution.

The limitations of this research are considered to relate to the primary data collection. Most of the analysis was based on processing the digital elevation model. The DEM used here was created from satellite data rather the on-site measurements. This creates issues regarding its accuracy. Since field measurements to create a DEM are very expensive and require a long period of time, it is suggested that

measurements from unmanned aerial vehicles could be used in similar research.

The present methodology could be used to aid the implementation of policies in the framework of the United Nations' Sustainable Development Goal regarding sustainable consumption and production (SDG 12).

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**Data availability** The authors declare that the data supporting the findings of this study are available within the paper, its supplementary information files, and the Aristotle University of Thessaloniki Forest Fund (<http://uniforest.auth.gr/>). The GIS files from the analysis are available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** The authors have no competing interests to declare that are relevant to the content of this article.

**Ethical approval** This manuscript is the authors' own original work, which has not been previously published elsewhere. The paper is not currently being considered for publication elsewhere. It reflects the authors' own research and analysis in a truthful and complete manner. All authors have been personally and actively involved in substantial work leading to the paper and will take public responsibility for its content. We agree with the above statements and declare that this submission follows the policies of the *Euro-Mediterranean Journal for Environmental Integration* guide for authors.

**Consent to publication** All authors consent to the publication of the manuscript in the *Euro-Mediterranean Journal for Environmental Integration* (EMJE), should the article be accepted by the Editor-in-Chief upon completion of the review process.

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