Original scientific paper

A Methodological Approach Exploiting Modern Techniques for Forest Road Network Planning

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Abstract

A well-developed road network allows all forest activities, including wood harvesting, firefighting and recreational activities. However, forest road construction and maintenance involve economic and environmental costs. For these reasons, forest road network planning is a fundamental phase of forest management, maximising the benefits and reducing costs and impacts. Thanks to modern technologies in data collection both for terrestrial and forest characteristics, new methods and tools have been developed to improve and facilitate road planning. The aim of this study was the development of a Decision Support System for helping managers during forest road network planning, exploiting Multi-Criteria Analysis, an Analytic Hierarchy Process and Geographic Information Systems. Three steps characterised the study:

- ⇒ *an in-depth survey of the existing forest road network*
- ⇒ *an accessibility evaluation, based on a commonly applied Italian definition, taking into account the morphological characteristics of the land*
- ⇒ *an estimation of the accessibility requirements through the analysis of experts' opinions, defined as Road Needs Index, based on different factors*

These phases were applied to a forest property located in northern Italy, and some improvements were proposed simulating a manager's approach during planning. The results showed interesting features in accessibility evaluation, which identified three different classes of accessibility, represented in a map. The estimation of Road Needs Index assigned a class regarding road requirements to each forest management unit: »low«, »medium«, »high« and »very high«. This information was merged, becoming a useful tool to identify the forest areas with the highest problems in relation to the forest road network.

Keywords: forest management, GIS, Analytic Hierarchy Process, accessibility, road needs, Decision Support System

1. Introduction

A sustainable perspective of forest management cannot ignore careful and accurate forest road network planning (Çalişkan 2013, Hippoliti 1997, Hippoliti 1976). A forest road network traditionally ensures access to forests and grazing lands, allowing forest operations and other productive activities. In the last decades, the increasing importance of the multi-functionality of forests has highlighted the key role of forest road management for tourism and recreational tasks (Gumus et al. 2008, Chirici et al. 2003). Moreover, forest roads allow access to remote areas in case of natural hazards (Enache et al. 2013) and are a fundamental infrastructure in extinguishing forest fires (Hayati et al. 2012). Construction characteristics should be different, depending on the kind of machines that are expected to run on different road branches. In particular, width, slope and radius of curvature are the most important elements for forest roads that can limit vehicles trafficability (i.e. dimensions and payload of vehicles). The quality of roads is related to building and maintenance quality, in terms of both techniques and materials, and it can vary during road lifespan (Kiss et al. 2015). Considering these aspects, an accurate road network plan is mandatory to allow the best efficiency and cost effectiveness of forest roads for all forest activities. Despite the essential role of forest roads in forest management, there are several potential negative effects in relation to these infrastructures. Despite the reduced width and excavation volume of a forest road in comparison with public roads, several environmental impacts relating to its construction, maintenance and use should affect this infrastructure (Trombulak and Frissell 2012, Avon et al. 2010, Demir 2007, Delgado et al. 2007), especially taking into account the natural context where it is located. However, these impacts can be reduced thanks to accurate planning and management (Akbarimehr and Naghdi 2012). Furthermore, forest roads should also be considered as ecosystems with an active role in the forest environment, which is not necessarily negative (Lugo and Gucinski 2000). For these reasons, a well-designed and well-developed road network plan must support the forest management plan to permit the best maintenance and enhancement of the road network, focused on the real management needs, through an integrated information exchange. Taking into account different interests related to forests, many analyses under various viewpoints have to be considered during planning. The main aspects under consideration should regard technical, economic and environmental issues. A technical approach identifies the strengths and weaknesses in the current road network to permit the best application of the management plan. Economic implications always have fundamental impacts; in the forest sector, the construction of a road is a significant cost (Ghajar et al. 2012, Samani and Hosseiny 2010) and accurate planning permits optimization of the cost effectiveness of road network management and enhancement. There are some fundamental steps that characterise a well-developed forest road network plan.

⇒ a complete knowledge of the actual conditions of each road segment in the entire network examined, both in terms of construction characteristics and maintenance conditions

⇒ a cautious evaluation of the actual accessibility state of different forest areas

⇒ an evaluation concerning the real needs of forest roads i.e. at management unit level in different sub-areas of the managed area, considering all of the functions provided by the analysed forest, such as wood production, hydrogeological protection, nature conservation, tourist interests and landscape tasks

The best system in forest management planning, where different needs have to be considered, is the development of a Decision Support System (DSS). In the last few years, this system has made possible an organised and integrated overview of relevant parameters related to forest functions, helping forest managers in decision processes (Vacik and Lexer 2014). In this context, considering the huge number of variables to be considered to represent the main interests related to forest multi-functionality, the approach of a Multi-Criteria Analysis (MCA) is recommended (Çalişkan 2013, Sacchelli et al. 2013). Moreover, the Analytic Hierarchy Process (AHP) (Saaty 1980) has been, and continues to be, one of the most common DSSs in defining the priority of different parameters considered, organising them in a hierarchy (Çalişkan 2013). Furthermore, Geographical Information Systems (GISs) play a key role in managing and displaying terrestrial data for spatial forest planning (Zeki Baskent and Keles 2005) and specifically also in forest road planning (Najafi and Richards 2013, Hayati et al. 2012, Mohtashami and Bergkvist 2012, Dean 1997). These approaches and technologies are widely used in forest planning under a sustainable perspective (Ducey and Larson 1999, Miettinen and Hämäläinen 1997) with a huge number of studies based on multi-criteria and hierarchical approaches, also on the specific topic of forest road planning (Pellegrini et al. 2013, Ghajar et al. 2012, Samani and Hosseiny 2010). Because of the integration between terrestrial data and information included in the forest management plan, a valuable road network plan, which takes into account the most important aspects of road management, can be developed. With such information, it is possible to make informed choices in road maintenance, enhancement and building. To summarise, short-term needs should not be the main influence in the construction of a forest road, but the intervention should be integrated in mid/long-term planning, to maximise the related functionality and economic benefits, minimising the environmental impacts. The aim of this work was the development of an MCA integrating GIS and AHP to obtain a DSS with reliable information regarding accessibility and road needs, in a case study area in northern Italy. Moreover, an evaluation of the obtained results was performed; the results were used in simulating a forest manager's interpretation and identifying weaknesses in the road network. Hypotheses for enhancement and improvements in the analysed forest road network were defined and suggested to the managers.

2. Materials and methods

The study area was Paneveggio forest, an alpine public property located in the Autonomous Province of Trento, in northern Italy. The property has a total

Table 1 Road classification following Italian standards

		Road for trucks		Road for tractors
		Main	Secondary	
Road width	Minimum	3.5 m	3.0 m	2.5 m
	Prevalent	5–6 m	4–5 m	3–4 m
Slope	Optimum	3–8%	3–8%	3–8%
	Max. average	10%	12%	14%
	Max. for short stretches	14%	18%	20 (25)%
	Max. counter slope*	10%	12%	14%
Minimum curvature radius in hairpin turns		10 m	7 m	5 m

* counter slope is defined as a grade that is opposite to the general running grade of a road, i.e. the slope of the road section/s that tractors or trucks have to cover loaded

area of 4300 ha, of which 2803 ha are forests. Paneveggio is entirely included in a mountainous area above 1300 m above sea level. Characteristic tree species are spruce (*Picea abies* (L.) H. Karst), larch (*Larix decidua* Mill.) and Swiss stone pine (*Pinus cembra* L.). A close-to-nature silviculture is applied in this area and the average annual yield is 6000 $m^3 y^{-1}$ of roundwood. Paneveggio is included in the »Provincial Natural Park of Paneveggio and Pale di San Martino«. The study was divided into three main parts to organise data collection and processing in sequential steps:

⇒ forest road network analysis
⇒ accessibility analysis
⇒ evaluation of forest road needs

These steps are described and illustrated below.

2.1 Forest road network analysis

At this stage, the objective was to collect all useful information regarding characteristics of the network, to implement an up-to-date database with geographical information, construction characteristics and maintenance level of each forest road. Each forest road was surveyed by car and several types of information were collected. With a set of basic instruments and a portable GPS, a survey form was filled in with the following main information: co-ordinates and altitude of starting and ending points, total length, maximum and average slope, prevalent and minimum width, minimum curvature radius of hairpin turns. Moreover, accessory elements such as water-bars, cross-drainage culverts, etc. were counted and described. For each road, a general description, an evaluation of maintenance conditions and the identification of criticisms were added to the form and then to the dataset. All of the collected information was implemented on a GIS platform (both ArcGIS 9.3 and QGIS 2.10 software were used) and a shape file with up-to-date information for each road was obtained. Roads were represented as lines, merged by nodes in each road intersection. A Digital Terrain Model (DTM) and orthophotographs were helpful during graphic representation of forest roads to correct the errors in accuracy made by the portable GPS during the field survey. Because of the dimensional characteristics collected, it was possible to classify each road following the Italian classification suggested by Hippoliti (1976), which is related to the kind of machine that could drive on the road. Characteristics of the roads are reported in Table 1.

All of the collected information was organised in a specific geo-referred database. The total length and road density (m ha^{-1}) were calculated.

2.2 Accessibility analysis

In this phase, an in-depth analysis of forest accessibility was developed by means of GIS, thanks also to the information collected and organised in the first step of this work. First of all, it was necessary to define the criteria of forest accessibility in relation to forest roads. The method based on the access time, suggested by Hippoliti (1976), was applied in detail. This method has been applied in other studies (Grigolato et al. 2013, Cavalli and Grigolato 2009, Chirici et al. 2003), because it is functional in mountainous conditions, and it takes into consideration terrain slope variations. Hippoliti (1976) defined three different accessibility classes based on the time required for a forest worker to make a round trip on foot from the nearest road to a given point in the forest. This time was called the »access time«. Hippoliti assumed an average walking speed for a worker in forest of 4 km h^{-1} on flat terrain, and a walking speed of 400 m_a h^{-1} on steep terrain, where m_a is the differential levelling in metres. When the access time is up to 30 minutes (for going in the morning and coming back at the end of workday), the area is classified as »served«, while when it is between 30 minutes and two hours, it is »barely served«. When a worker spends more than two hours reaching the work site, the area is considered as »not served« by the forest road network. This concept was introduced in the '70s, when the manpower price in Italy was »very low«. Nowadays, considering the cost of manpower, it is not economically viable to spend two hours to reach the work site. For that reason, in this work Hippoliti's approach was modified in time ranges, reducing the maximum access time to one hour for

Table 2 Accessibility categories based on a revised definition of Hippoliti

Accessibility	Access time (return trip)	Distance in flat terrain (when slope < 10%)	Differential levelling (when slope≥10%)
»Served«	Up to 30'	Max. 1000 m	Max. 100 m
»Barely served«	Between 30' and 60'	Max. 2000 m	Max. 200 m
»Not served«	More than 60'	More than 2000 m	More than 200 m

»barely served« areas. The revised accessibility characteristics are summarised in Table 2.

Three different methods were implemented in the Paneveggio forest to calculate and graphically represent the degree of accessibility. The classical method, based on a field survey and manual representation on maps, was implemented to identify the second best application in terms of accuracy and reliability. The descriptions of each method are reported below.

2.2.1 »Method H« manual approach

»Served« and »barely served« areas were manually drawn starting from each road branch and considering altitude gaps (100 m for »served« and 200 m for »barely served« areas). Once the draft accessibility map was made, a field survey permitted correction of the map identifying natural barriers that impede access to some areas, e.g. cliffs and deep gullies. Finally, the results were manually reported on a GIS platform to obtain a digital map, comparable with the results of the other methods.

2.2.2 »Method A« travel time

This was the first GIS approach applied in this study for accessibility estimation. Hippoliti's definition for accessibility could be described taking into account the travel time or travel distance. In this method, the travel time was considered to determine the accessibility class for each point in the forest property (Chirici et al. 2003). This operation required several steps and information. A DTM with a resolution of 5´5 m created from LIDAR data, and the road network map previously developed (see Section 2.1) were used as starting information. A »Cost Distance« tool was applied to calculate the accessibility degree of the forest surface. In particular, this tool is a procedure for determining least cost paths across continuous surfaces, typically using grid representations (de Smith et al. 2015). In this study, Cost Distance identified the surface, around each forest road, with a maximum cost in terms of time of walking transfer for a forest worker. Therefore, several steps were made to obtain a »cost-map« including the information concerning the crossing time for each pixel, which strictly depends on the slope gradient:

⇒ slope map creation, starting from the DTM, in raster format containing the slope gradient in % for each pixel, $p_{\%}$

⇒ differential levelling (d), covered for each pixel, was calculated considering a horizontal distance (d_0) of 6 m (the average of the side of the pixel, 5 m, and the diagonal, 7 m), using the formula:

$$\text{differential levelling} = d = \frac{p_{\%} \cdot d_0}{100} \qquad (1)$$

⇒ »d« was reclassified with high value (900 m) to exclude extreme slopes (>100%), that could not be crossed by walking. For slopes lower than 10%, a fixed value of 0.6 m was assigned to obtain efficient results for flat terrains, too

⇒ considering the climbing speed of 400 $m_a\,h^{-1}$, corresponding to 0.1 $m_a\,s^{-1}$ (t_u), a raster containing information regarding the time of pixel crossing was made by the following equation:

$$\text{pixel crossing time} = t_{pc} = \frac{d}{t_u} = \frac{d}{0.\bar{1}} \qquad (2)$$

⇒ starting from the vector file of the forest road network, a raster file representing presence/absence of roads was created

⇒ the Cost Distance tool was applied to define the »served« and »barely served« areas, starting from the raster of road presence and the cost-map previously created, applying the time limits as maximum cost (15 minutes and 30 minutes for »served« and »barely served« areas, respectively)

2.2.3 »Method B« fraction of the maximum distance

In the previous method, »Cost Distance« was applied considering the travel time. In this case, a method that interprets the accessibility definition considering the travel distance was developed. As explained in Section 2.2, on flat terrain we considered the linear distance covered, while on a slope we considered the change of altitude between the starting point at the roadside and the work point in the forest. A DTM of 5´5 m in resolution guaranteed the morphological information. The Cost Distance procedure was also applied in this case, and several steps were necessary:

⇒ a slope map ($p_{\%}$) based on DTM was created

⇒ the slope map was reclassified, as in »method A«, to obtain a unique »cost-map« efficient on both slope and flat terrain. Therefore, the values

»10« were assigned to all the pixels characterised by a slope up to 10%, and the value »99999«, to all the pixels with a slope higher than 100%

⇒ a »weight« was given to each pixel, which was determined as the ratio between the maximum distance (d_{max}) on flat terrain (1000 m) and the horizontal distance ($Df(p_{\%})$) corresponding to the maximum differential levelling (d_{max}) (»served« = 100 m, »barely served« = 200 m) on a terrain with the slope of the pixel taken into account. Finally, the formulas for weight calculation were the following:

$$\text{weight} = w = \frac{D_{max}}{D_{f(p_{\%})}}, \quad D_{f(p_{\%})} = \frac{100 \cdot d_{max}}{p_{\%}} \qquad (3)$$

⇒ the final cost-map was obtained by multiplying the weight value by the pixel size

⇒ starting from the vector file of the forest road network, a raster file representing presence/absence of roads was created

⇒ starting from the road raster (presence/absence) and the cost-map previously created, applying the distance limits as maximum cost (1000 m and 2000 m for »served« and »barely served« areas, respectively), the Cost Distance tool was applied defining the »served« and »barely served« areas

2.2.4 »Method C« fixed distance buffer

This is an expeditious approach, which did not consider Hippoliti's definition of accessibility. It was implemented to compare a quick method with the other models described. It simply drew a buffer at a fixed distance from each road branch. Several examples of this accessibility evaluation have been developed in other studies, considering different distances in relation to the type of machines and techniques applied. Some studies set a unique limit value, e.g. 300 m without slope considerations (Bååth et al. 2002), and 3 km but limited to the first slope class (max. 20%) (López-Rodríguez et al. 2009). Moreover, in other studies, different classes with a varying distance were considered, comparing buffers within 150, 200 and 250 metres from the road (Pentek et al. 2008). In this study, two buffers were applied, the first in a range of 100 m from the road and the second in a range of 300 m. The first corresponds to the »served« area, which was identified with the operative distance generally considered for extraction with tractor and winch. The second one was assumed as the »barely served« area, which corresponds to the operative distances of a lightweight cable-yarder.

Finally, a comparison between the different methods was made. »Method H« was considered as »truth« to have a reference for comparison.

2.3 Evaluation of forest road needs

Thanks to the previous analysis, the accessibility degree for all forest management units was available. This was important information, but it needed to be integrated with another analysis, in a typical MCA perspective, to obtain a complete set of information useful for roads management. In particular, it was fundamental to support accessibility information with the real needs of roads for each forest management unit. The »needs of roads« (or »needs of accessibility«) aimed to identify the accessibility requirements in different areas, concerning different characteristics of forest management units and the related silvicultural prescriptions applied. Effectively, forest located at an altitude close to the upper tree line, with low tree growth and managed under a protective perspective, generally requires a lower accessibility level than others located in a more fertile area, with high yield, and managed under a productive perspective. In this context, a GIS-based method for evaluating the forest needs in terms of accessibility was developed. It was assumed that forest operations would be the forest-related activities characterised by the highest accessibility requirements, compared with other services provided by the forest, and activities carried out inside it. Therefore, the methodology was developed considering factors related to forest productivity. On the basis of Paneveggio's forest management plan, a set of data was chosen as factors useful for determining the forest-road needs. Three categories were identified as more suitable than the others considering their reliability and the impact on this study: growing stock (*GS*), site fertility class (*FC*) and productive potential index (*PPI*) for high forests. Other factors were discarded for specific reasons, e.g. the annual volume increment, which should be a good indicator characterising a forest management unit in terms of productive capacity. In our case, the increment information presented some out-of-scale values, presumably attributable to mistakes in reporting, which did not guarantee a good reliability level. In particular, the three cited factors were chosen because:

⇒ *GS* represented a reference point in a short-term productivity perspective

⇒ *FC*, which was divided into nine classes, from the most fertile (class »1«) to the least fertile (class »9«), assigned to each forest management unit. It was chosen for representing a fixed condition along the time regarding the production capacity of each management unit

⇒ *PPI*, this was a classification made by a pool of experts regarding the whole Province of Trento. Following different parameters, including the main tree species, hydrogeological risks and environmental significance, they assigned to forest sub-areas a synthetic value representative of their productive potential. This index was divided into nine classes, from the lowest productive potential (class »1«) to the highest (class »9«). This factor was chosen because it was relevant from a long-term management perspective.

To calculate a »road needs index« (*RNI*), after normalization, the factors were merged by means of a weighted sum. To assign a »weight« to each factor, an Analytic Hierarchy Process (AHP) was applied to the results of local forest expert interviews. Each factor was normalised (in a range between 0 and 1) following the processes explained below:

»Growing Stock« (*GS*): considering the distribution of *GS* values, we applied an exponential function for *GS* values up to 700 $m^3\,ha^{-1}\,y^{-1}$, with increasing values from 0 to 1; for *GS* values higher than 700 $m^3\,ha^{-1}\,y^{-1}$, the normalised value assigned was always 1:

$$GS_{norm} = \begin{cases} -0.00000198835GS^2 + 0.00280713GS + 0.0093\ ,\ for\ 0 \le GS \le 700 \\ 1\ ,\ for\ GS > 700 \end{cases} \quad (4)$$

»Fertility Class« *(FC):* forest management unit distribution in fertility classes showed a reduced frequency in the most fertile classes. For this reason, this factor was normalised assigning value 1 to the first three classes, and a linear regression was applied for the classes from the fourth to the ninth, with decreasing values from 1 to 0:

$$FC_{norm} = \begin{cases} -\frac{1}{6}FC + \frac{3}{2}\ ,\ for\ FC > 3 \\ 1\ ,\ for\ 1 \le FC \le 3 \end{cases} \quad (5)$$

»Productive Potential Index« *(PPI):* a linear regression was applied assigning increasing values from the lowest potential to the highest, in the range 0 to 1:

$$PPI_{norm} = \frac{1}{8}PPI - \frac{1}{8} \quad (6)$$

Sixteen forest experts, including forest managers and Provincial Forest Service members, were interviewed to collect their personal opinion on the importance of the three factors previously described regarding forest management, with special attention on the topic of forest roads. In particular, a compilation of questions, based on a comparison of the three factors, was submitted to the experts by a personal interview. Following AHP concepts, personal opinions were implemented by Expert Choice® software to obtain an impartial result on the importance of analysed factors for forest road management. The software compared the answers given by people interviewed and provided the »weight« value in% for each factor.

Finally, one raster file was calculated for each factor involved in the analysis. The *RNI* map was calculated by the weighted sum between GS_{norm}, FC_{norm} and PPI_{norm}:

$$RNI = w_{GS} \quad GS_{norm} + w_{FC} \quad FC_{norm} + w_{PPI} \quad PPI_{norm} \quad (7)$$

where *wGS*, *wFC* and *wPPI* were the weights obtained for *GS*, *FC* and *PPI*, respectively.

The result was a map of the Paneveggio forest in which each pixel was classified in relation to accessibility requirements. The Paneveggio forest was divided into four road needs classes:

»Low«: with $RNI < 0.25$,

»Medium«: with $0.25 \le RNI < 0.50$,

»High«: with $0.50 \le RNI < 0.75$,

»Very high«: with $RNI \ge 0.75$.

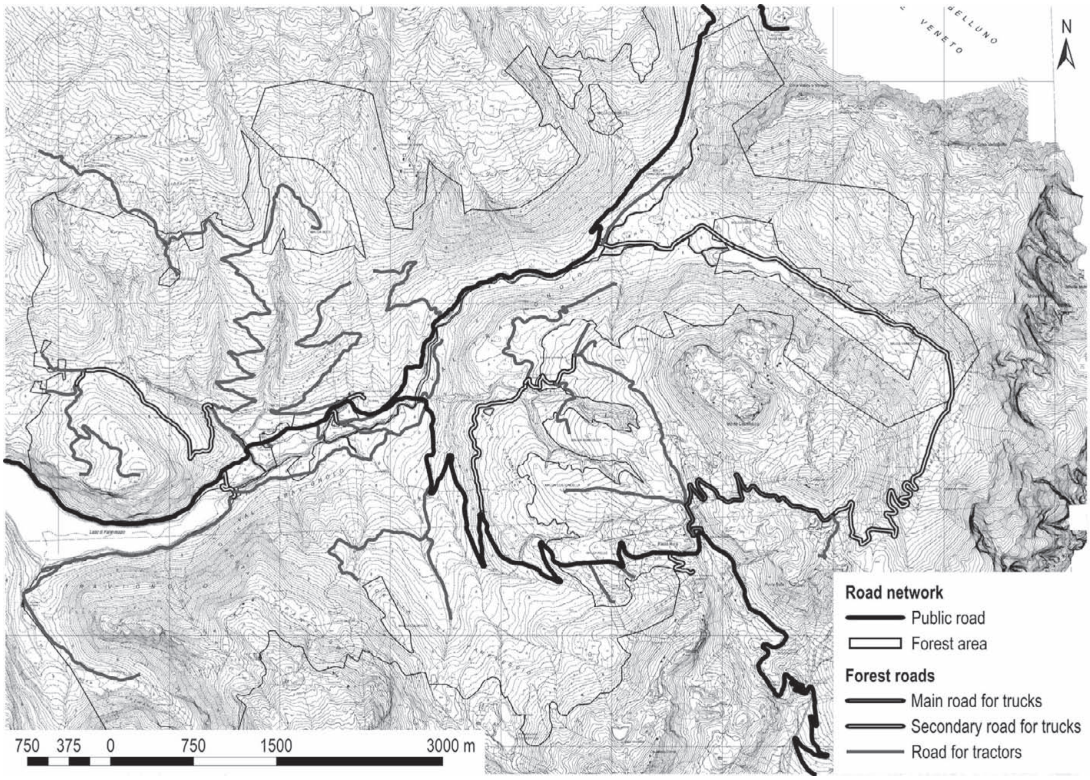

Fig. 1 Paneveggio forest road network

3. Results

3.1 Forest road network analysis

The first step of this study collected information regarding the state of the forest road network. A shape file was created and the road network is represented in Fig. 1. In the related database, all of the information collected and cited in Section 2.1 was recorded. The total length of road network within the forest area (2803 ha) was 37.1 km, corresponding to a density of 13.2 m ha^{-1}, while in the overall property (4366 ha) there were 52.4 km of roads, with a density of 12 m ha^{-1}. According to the Italian classification, the majority of forest roads (69% of total, 36 km) were classified as »Road for tractor«, while 25% were classified as »Secondary road for truck« and only 6% were included in the category »Main road for truck«.

3.2 Accessibility analysis

The four methods described in Section 2.2 were implemented and compared. Results regarding the surface distribution between the three accessibility classes are reported in Table 3. A comparison between »Method A« (Fig. 2), »Method B« (Fig. 3) and »Method C« (Fig. 4), considering »Method H« (Fig. 5) as reference, was developed to evaluate the correspondence rate. In particular, the maps were overlapped and compared, identifying the percentage of pixels with the same accessibility class assigned (correspondence) and the others, where the model assigned different classes. The results showed that correspondences of 83.1%, 87.2% and 51.5% were calculated for methods A, B and C, respectively, using »Method H« as the reference.

3.3 Evaluation of forest road needs

The AHP results defined the values for the »weights« to be used in the *RNI* calculation. In par-

Table 3 Surface distribution in accessibility classes identified by means of four analysed methods

	»Served«		»Barely served«		»Not served«	
»Surface«	%	ha	%	ha	%	ha
»Method H«	56.2	1574	20.0	562	23.8	667
»Method A«	54.7	1534	21.2	594	24.1	675
»Method B«	60.2	1689	21.4	599	18.4	515
»Method C«	26.8	750	34.2	960	39.0	1093

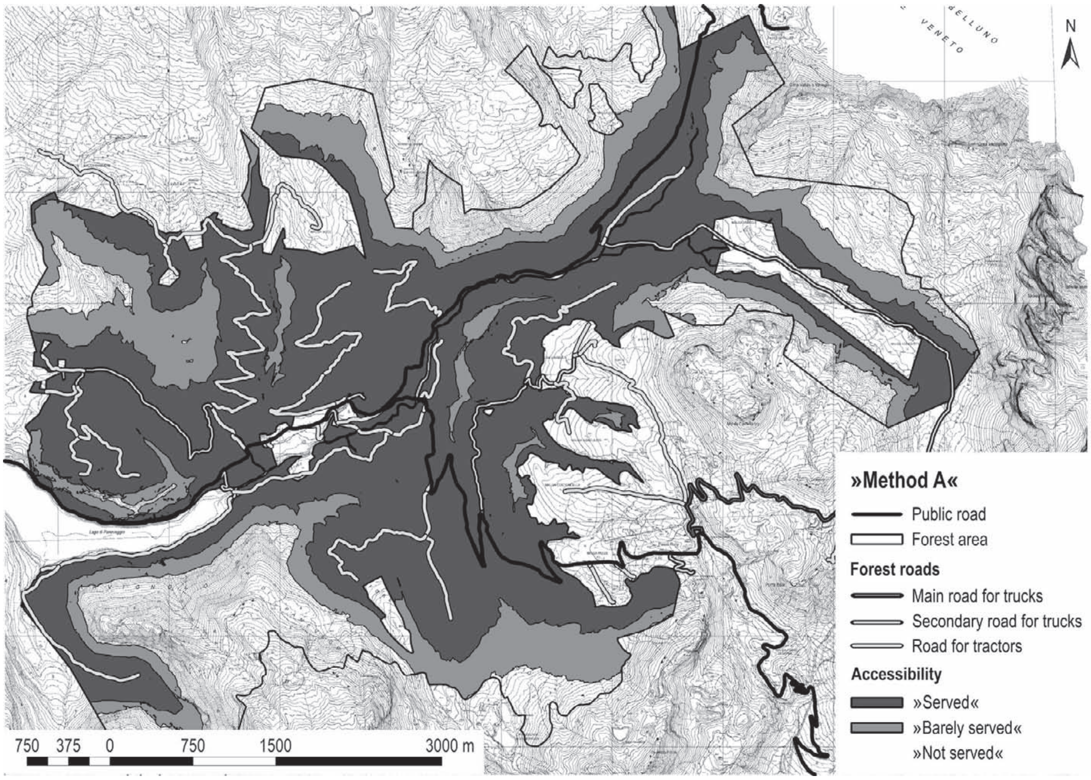

Fig. 2 Results of »Method A« applied to Paneveggio forest

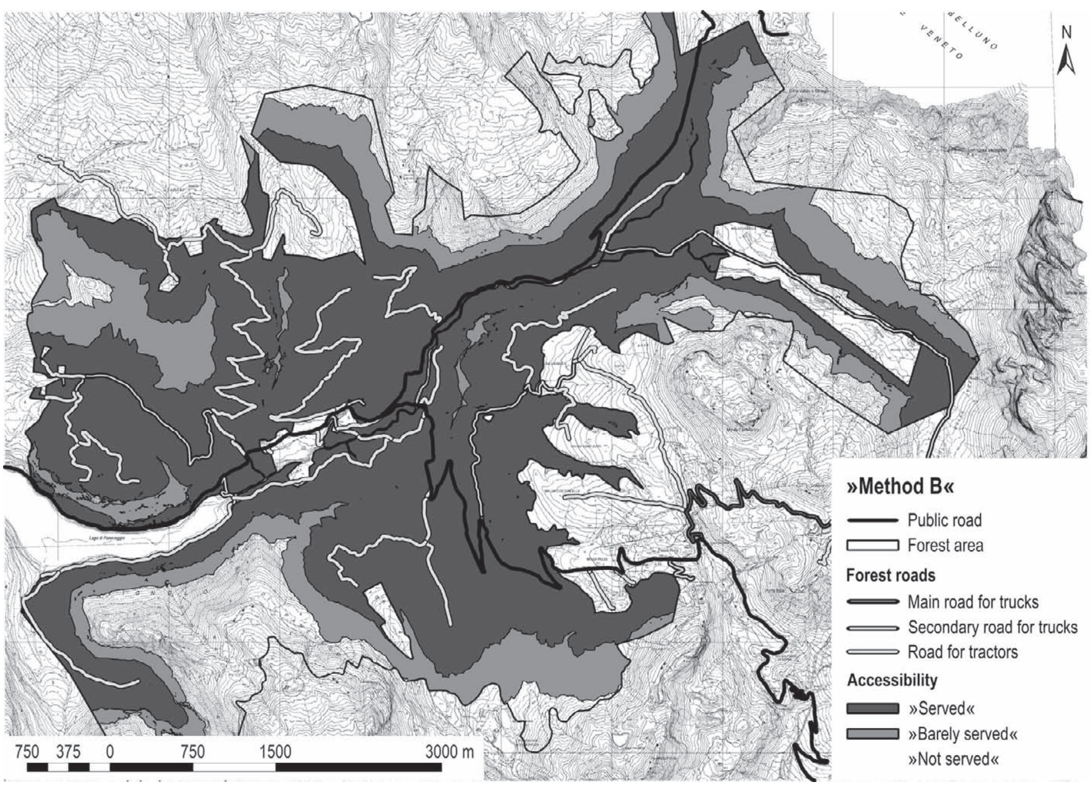

Fig. 3 Results of »Method B« applied to Paneveggio forest

Table 4 Forest area distribution based on *RNI*. For each *RNI* class, the distribution of the area in each of the current accessibility classes is shown

			Total	At-present accessibility class		
				»Served«	»Barely served«	»Not served«
Road Needs Index	»Low«	ha	75.7	0.0	22.4	53.3
		%	2.7	0.0	0.8	1.9
	»Medium«	ha	765.2	185.0	238.3	341.9
		%	27.3	6.6	8.5	12.2
	»High«	ha	1202.5	857.7	274.7	70.1
		%	42.9	30.6	9.8	2.5
	»Very High«	ha	759.6	644.7	64.5	50.4
		%	27.1	23.0	2.3	1.8

ticular, the elaboration of experts' answers showed that the most important factor was the *GS*, with a weight of 45%, while weights of 30% and 25% were determined for *FC* and *PPI*, respectively. The final formula applied to each forest management unit in calculating the *RNI* was:

$$RNI = 0,45 \quad GS_{\text{norm}} + 0,30 \quad FC_{\text{norm}} + 0,25 \quad PPI_{\text{norm}} \qquad (8)$$

Summarised information on *RNI* distribution of the total surface, also in relation with the current accessibility results, is reported in Table 4.

Fig. 6 gives a graphical representation of the *RNI* results, distributed following four classes established in Section 2.3.

Overall results were interpreted to identify the areas in terms of road accessibility. Taking into account all of the results, two new road branches were proposed. The two hypotheses are reported in Fig. 7.

4. Discussion

Due to different analyses performed, different topics were investigated in this study and useful information was obtained to facilitate and improve the decision processes related to forest road network planning. Analysis of the existing road network highlighted the predominance (69%) of forest roads only suitable for the transit of tractor and trailer, while 25% were roads with better characteristics in terms of width, radius of

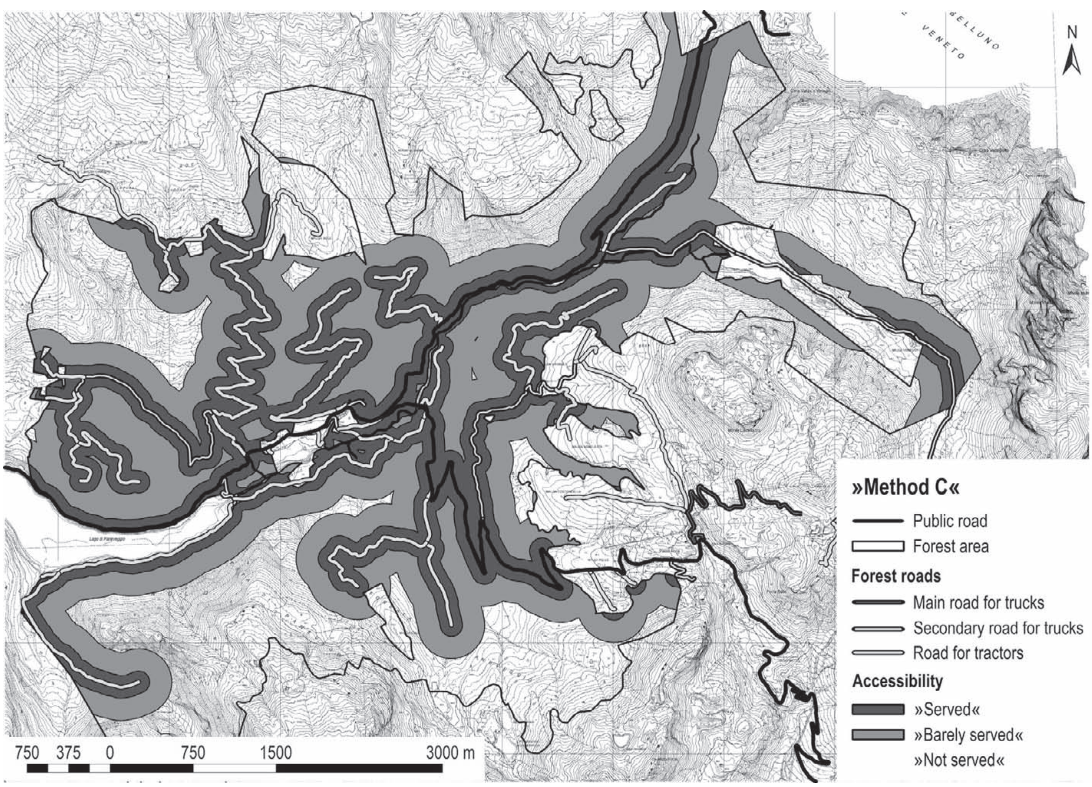

Fig. 4 Results of »Method C« applied to Paneveggio forest

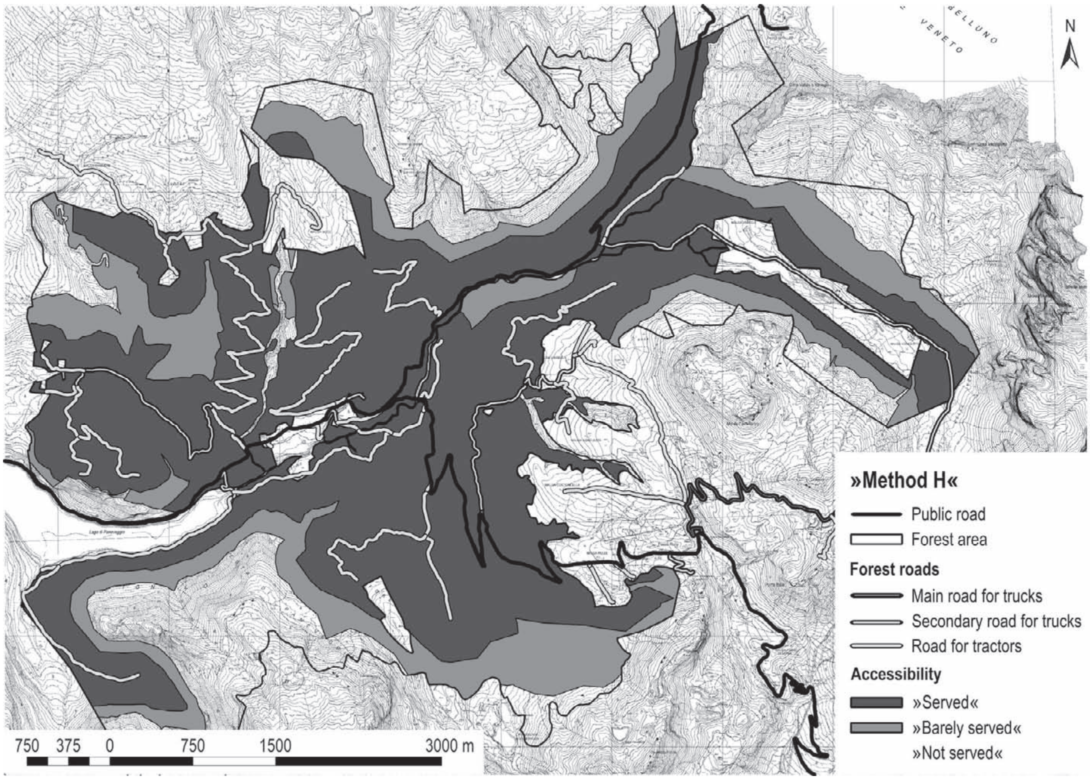

Fig. 5 Results of »Method H« applied to Paneveggio forest

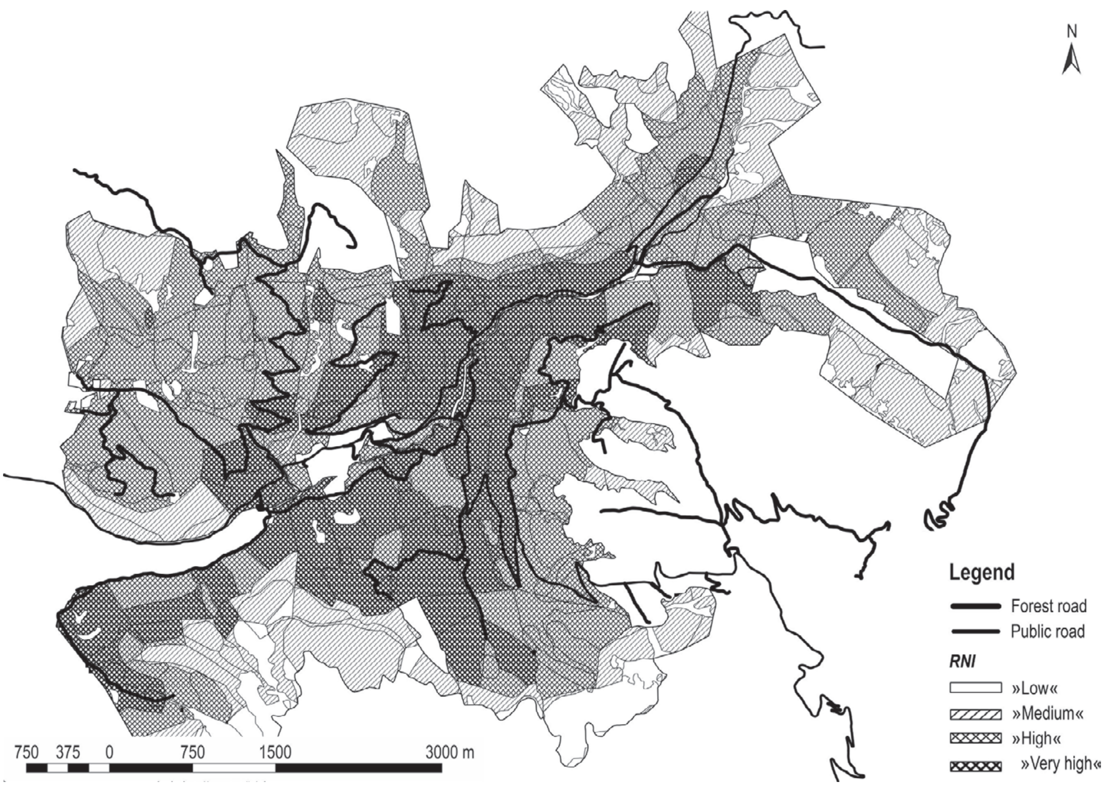

Fig. 6. Distribution of forest management units in classes depending on *RNI*

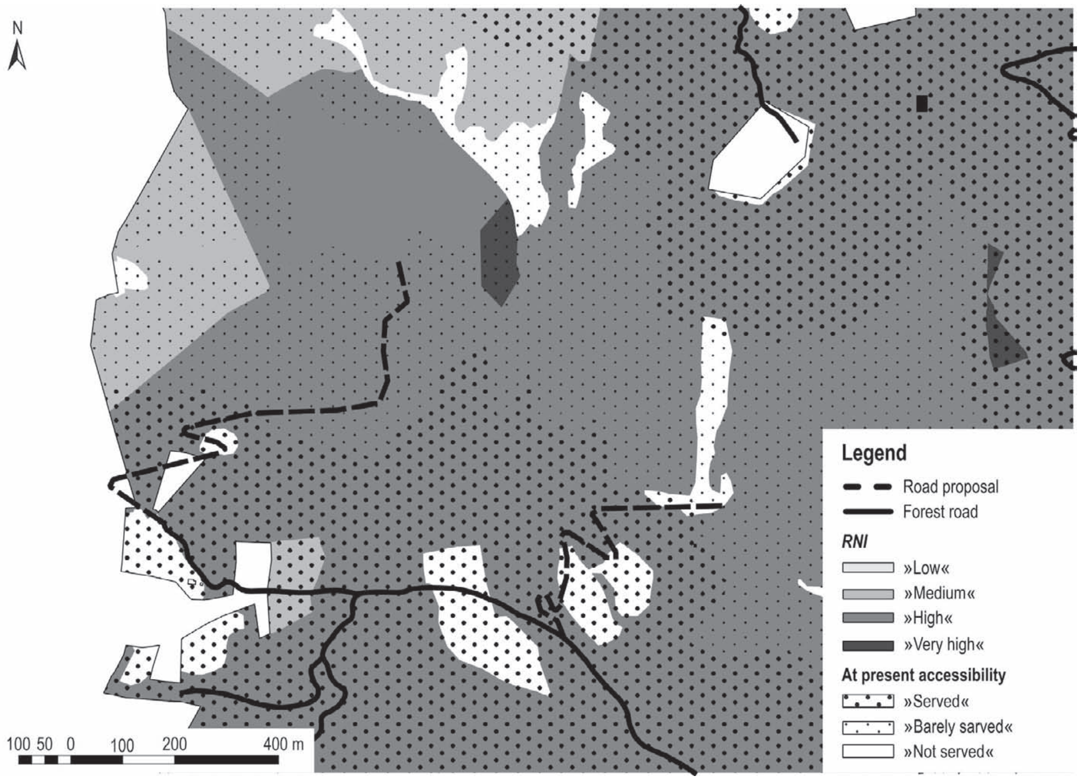

Fig. 7 Proposals for two new forest roads

curvatures and slope; only 6% of roads could allow the transit of heavy trucks. This information should suggest the enhancement of the main forest roads to improve and rationalise wood transport by means of heavy trucks instead of tractors and trailers. The slope is a crucial factor in accessibility estimation. In mountainous areas, the slope heavily influences the accessibility (Cavalli and Grigolato 2009) and strongly affects the logging system and costs of forest operations (Hippoliti 1997). In this study, the accessibility analysis added essential information regarding the rationality in forest roads distribution around the forest property. Comparing the applied methods, »Method C« showed the worst performance, in terms of correspondence, in comparison with results obtained by »Method H«, which was taken as the reference. »Methods A« and »B« had similar responses; »Method A« obtained better results than »Method B« considering the general surface percentage allocated to the three different categories, which were very similar in value to »Method H«. On the other hand, »Method B« showed better accuracy than »Method A«, considering the correspondence in pixel allocation. This similarity was expected, considering the similar approach used in the two methods. However, accuracy was considered as the main objective in identifying the best method for accessibility estimation, and »Method B« had the better performance in this sense. It showed a »high« rate of »served« management units in Paneveggio forest (about 60% of the total) and a limited »not served« area (18%). In this context, introducing the evaluation of the real needs of forest roads in different areas, especially regarding »barely« and »not served« areas, could give an added value to the roads planning process according to the multi-criteria approach. As reported in Table 4, »not served« areas mainly referred to forest management units with a »low« or »medium« *RNI*, while only a limited area with »high« and »very high« needs was »not served«. Regarding »barely served« management units, there was a reasonable rate of forest with »medium« and »high« *RNI*. In this case, an enhancement of the road network should improve accessibility conditions, optimising productivity in forest operations. Regarding the three factors analysed in the AHP, technicians focused their main interest on growing stock (weight: 45%), which is a factor influencing short-term decisions. Fertility class had an intermediate weight (30%), thus highlighting the attention of forest technicians also on long-term aspects, while the productive potential index (25%) received a quite low weight. In practice, *RNI* analysis took into account a balanced mix of information aimed both to short and long-term approaches for forest road network planning. However, the method could be improved through the implementation of more, or different, factors; in particular, the increments of volume should be considered when available to obtain a representative parameter related to stand productivity. Moreover, in *RNI* analysis, different solutions or alternatives could be implemented to optimise the methods depending on management priorities. In the case of special needs, specific factors could be introduced into the *RNI* calculation formula, enlarging the analysis to specific topics. An example of that would be the use of indicators regarding wildfire risk, or tourism points of interest. In these cases, the *RNI* analysis could give useful information in addition to the ordinary needs, normally satisfied when the road network is functional for forest operations.

5. Conclusion

In this study, a methodological approach aimed to improve forest road network planning was developed and applied to a forest property. MCA and AHP criteria were applied by means of GIS, exploiting terrestrial information and forest characteristics. The state and accessibility requirements in a forest area have key roles in optimising road network management. The analysis developed in this study could be a real added value for managers during planning. In particular, the examined methods facilitate objective forest road planning, which permits optimisation of resources and avoids the building of a useless road and/or oversized road network. Enhancement of the forest road network, through well-defined improvements, guarantees the correct management of the forest, allowing all of the forest services, such as wood production, hydrogeological protection, tourism use and habitat conservation. In practice, a well-planned and well-realised road network maximises the efficiency of all forest activities, minimising the costs, both economically and environmentally. The approach described and achieved in this study perfectly fit in this perspective, reporting fundamental information useful for sustainable maintenance and development of the forest road network.

6. References

Akbarimehr, M., Naghdi, R., 2012: Reducing erosion from forest roads and skid trails by management practices. Journal of Forest Science 58(4): 165–169.

Avon, C., Bergès, L., Dumas, Y., Dupouey, J.L., 2010: Does the effect of forest roads extend a few meters or more into the adjacent forest? A study on understory plant diversity in managed oak stands. Forest Ecology and Management 259(8):1546–1555.

Bååth, H., Gällerspång, A., Hallsby, G., Lundström, A., Löfgren, P., Nilsson, M., Ståhl, G., 2002: Remote sensing, field survey, and long-term forecasting: An efficient combination for local assessments of forest fuels. Biomass and Bioenergy 22(3): 145–157.

Çalişkan, E., 2013. Planning of forest road network and analysis in mountainous area. Life Science Journal 10(2): 2456–2465.

Cavalli, R., Grigolato, S., 2009: Influence of characteristics and extension of a forest road network on the supply cost of forest woodchips. Journal of Forest Research 15(3): 202–209.

Chirici, G., Marchi, E., Rossi, V., Scotti, R., 2003: Analisi e valorizzazione della viabilità forestale tramite GIS: la foresta di Badia Prataglia (AR). L'Italia Forestale e Montana 6: 460–481.

Dean, D.J., 1997: Finding optimal routes for networks of harvest site access roads using GIS-based techniques. Canadian Journal of Forest Research 27(1): 11–22.

Delgado, J.D., Arroyo, N.L., Arévalo, J.R., Fernández-Palacios, J.M., 2007: Edge effects of roads on temperature, light, canopy cover, and canopy height in laurel and pine forests (Tenerife, Canary Islands). Landscape and Urban Planning 81(4): 328–340.

Demir, M., 2007: Impacts, management and functional planning criterion of forest road network system in Turkey. Transportation Research Part A: Policy and Practice 41(1): 56–68.

Ducey, M., Larson, B., 1999: A fuzzy set approach to the problem of sustainability. Forest Ecology and Management 115(1): 29–40.

Enache, A., Ciobanu, V.D., Kühmaier, M., Stampfer, K., 2013: An Integrative Decision Support Tool for Assessing Forest Road Options in a Mountainous Region in Romania. Croatian Journal of Forest Engineering 34(1): 43–60.

Ghajar, I., Najafi, A., Ali Torabi, S., Khamehchiyan, M., Boston, K., 2012: An Adaptive Network-based Fuzzy Inference System for Rock Share Estimation in Forest Road Construction. Croatian Journal of Forest Engineering 33(2): 313–328.

Grigolato, S., Pellegrini, M., Cavalli, R., 2013: Temporal analysis of the traffic loads on forest road networks. iForest-Biogeosciences and Forestry 6(5): 255–261.

Gumus, S., Acar, H.H., Toksoy, D., 2008: Functional forest road network planning by consideration of environmental impact assessment for wood harvesting. Environmental Monitoring and Assessment 142(1–3): 109–116.

Hayati, E., Majnounian, B., Abdi, E., 2012: Qualitative evaluation and optimization of forest road network to minimize total costs and environmental impacts. iForest – Biogeosciences and Forestry 5(3): 121–125.

Hippoliti, G., 1997: Appunti di meccanizzazione forestale, Firenze: Società Editrice Fiorentina.

Hippoliti, G., 1976: Sulla determinazione delle caratteristiche della rete viable forestale. Italia Forestale e Montana – Italian Journal of Forest and Mountain Environments 6: 242–255.

Kiss, K., Malinen, J., Tokola, T., 2015: Forest road quality control using ALS data. Canadian Journal of Forest Research 45(11): 1636–1642.

López-Rodríguez, F., Atanet, C.P., Blázquez, F.C., Celma, A.R., 2009: Spatial assessment of the bioenergy potential of forest residues in the western province of Spain, Caceres. Biomass and Bioenergy 33(10): 1358–1366.

Lugo, A.E., Gucinski, H., 2000: Function, effects, and management of forest roads. Forest Ecology and Management 133(3): 249–262.

Miettinen, P., Hämäläinen, R.P., 1997: How to benefit from decision analysis in environmental life cycle assessment (LCA). European Journal of Operational Research 102(2): 279–294.

Mohtashami, S., Bergkvist, I., 2012: A GIS Approach to Analyzing Off-Road Transportation: a Case Study in Sweden. Croatian Journal of Forest Engineering 33(2): 275–284.

Najafi, A., Richards, E.W., 2013: Designing a Forest Road Network Using Mixed Integer Programming. Croatian Journal of Forest Engineering 34(1): 17–30.

Pellegrini, M., Grigolato, S., Cavalli, R., 2013: Spatial Multi-Criteria Decision Process to Define Maintenance Priorities of Forest Road Network : an Application in the Italian Alpine Region. Croatian Journal of Forest Engineering 34(1): 31–42.

Pentek, T., Pičman, D., Nevečerel, H., Lepoglavec, K., Poršinsky, T., 2008: Road network quality of the management unit Piščetak – GIS analysis. In Proceedings of the 3rd international scientific conference FORTECHENVI 2008, 45–53.

Saaty, T.L., 1980: The analytic hierarchy process: planning, priority setting, resources allocation. New York: McGraw.

Sacchelli, S., De Meo, I., Paletto, A., 2013: Bioenergy production and forest multifunctionality: A trade-off analysis using multiscale GIS model in a case study in Italy. Applied Energy 104: 10–20.

Samani, K., Hosseiny, S., 2010: Planning road network in mountain forests using GIS and Analytic Hierarchical Process (AHP). Caspian Journal of environmental sciences 8(2): 151–162.

de Smith, M.J., Goodchild, M.F., Longley, P.A., 2007: Geospatial Analysis. A comprehensive guide to principles. techniques and software tools. Leicester, UK: Matador, Troubador Publishing Ltd.

Trombulak, S.C., Frissell, C.A., 2012: Review of Ecological Effects of Roads on Terrestrial and Aquatic Communities and of Aquatic Ecological Effects of Roads on Terrestrial Commnunities 14(1): 18–30.

Vacik, H., Lexer, M.J., 2014: Past, current and future drivers for the development of decision support systems in forest management. Scandinavian Journal of Forest Research 29(1): 2–19.

Zeki Baskent, E., Keles, S., 2005: Spatial forest planning: A review. Ecological Modelling 188(2–4): 145–173.

Received: February 1, 2016
Accepted: April 4, 2016

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