

An eco-efficient and economical optimum evaluation technique for the forest road networks: the case of the mountainous forest of Metsovo, Greece

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Abstract The sustainable forest management can be achieved only through environmentally sound and economically efficient and feasible forest road networks and transportation systems that can potentially improve the multi-functional use of forest resources. However, road network planning and construction suggest long-term finance that require a capital investment (cash outflow), which would be equal to the value of the total revenue flow (cash inflow) over the whole lifecycle project. This paper emphasizes in an eco-efficient and economical optimum evaluation method for the forest road networks in the mountainous forest of Metsovo, Greece. More specifically, with the use of this technique, we evaluated the forest roads' (a) total construction costs, (b) annual maintenance cost, and (c) log skidding cost. In addition, we estimated the total economic value of forest goods and services that are lost from the forest roads' construction. Finally, we assessed the optimum eco-efficient and

economical forest roads densities based on linear equations that stem from the internal rate of return method (IRR) and have been presented graphically. Data analysis and its presentation are achieved with the contribution of geographic information systems (GIS). The technique which is described in this study can be for the decision makers an attractive and useful implement in order to select the most eco-friendly and economical optimum solution to plan forest road network or to evaluate the existing forest transportation systems. Hence, with the use of this method, we can combine not only the multi-objective utilization of natural resources but also the environmental protection of forest ecosystems.

Keywords Forest road networks · Forest transportation systems · Eco-efficient · Economical · Optimum · Evaluation

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Introduction

Several publications have appeared in recent years documenting that forest road network layout, transportation systems, and harvesting operations are strategic principles for the sustainable management and socioeconomic development of forest areas (Abdi et al. 2009; Akay et al. 2012; Epstein et al. 2001; Makhdoum 2008; Xie et al. 2010). Despite inherent difficulties associated with the planning and construction of forest road networks layout and transportation engineering, progress has been made recently thanks to the increased availability, widespread use, and accuracy of new technologies, high-

precision data as well as the improvements of optimization techniques (Gulci et al. 2017; Heinimann and Breschan 2012; Stükelberger et al. 2004; Stükelberger et al., 2007). Additionally, forest roads are influenced by many technical, economic, environmental, and social factors in order to offer the services what they are designed for (Epstein et al. 2007; Gumus 2009; Parsakhoo et al. 2010). Previous research has documented that forest operations remains a problematic issue due to the fact that they affect the structure of ecosystems and the dynamic of their services (Boston 2016; Ezzati et al. 2016; Fu et al. 2010; Jaafari et al. 2015; Pentek et al., 2008). Also, the forest roads' construction causes a great variety of primary or direct ecological effects as well as secondary or indirect impacts to the landscape ecology. The results of road constructions can be seen in all the abiotic and biotic components of terrestrial and aquatic ecosystems (Coffin 2007; Forsyth et al. 2006; Ibisch et al. 2016; Jordán-López et al. 2009; Ramos-Scharrón and MacDonald 2007; Robinson et al. 2010). Besides, the evaluation of forest ecosystem goods and services is a mandatory and a reliable piece of information for decision makers (Grêt-Regamey et al. 2008). Moreover, during the phase of planning and construction of forest roads, the method of assessing the road impacts on biodiversity (biodiversity impact assessment, BIA) with an approach based on the rarity of the ecosystem could be proved important (Geneletti 2003). Experts have seen that an integrating model, taking into account environmental criteria in optimizing the forest roads planning network without affecting the cost of construction of roads, is an important factor in forest management (Akay et al. 2008; Epstein et al. 1999; Hruza et al. 2013). Also, the forest roads planning should be carried out with the minimum total cost and should take under consideration the environmental impacts (Akay 2006; Hayati et al. 2012; Naghdi and Babapour 2009). In previous years, many researchers have published their work, presenting the optimal planning of harvesting, logging operations, transportation systems, and their management strategies that comprise the basic principle in order to minimize environmental impacts, as well as to satisfy the need for the utilization of forest resources (Bont 2012; Dietz et al. 1984; Epstein et al. 2006; Ghaffariyan et al. 2010; Hafner, 1971; Kuonen, 1983; Tampekis et al. 2015; Wegner, 1984; Zamora-Cristales et al. 2015).

The qualitative evaluation and optimization of forest road network that aim at the minimization of total life cycle costs and environmental impacts

are very important for the sustainable management of forests (Najafi et al. 2008; Stükelberger et al. 2006; Žáček and Klč 2008). Therefore, designers of forest operations should design timber harvesting activities after considering not only the efficiency costs but also their environmental impacts (Han et. 2015; Larsen and Parks, 1997; Parsakhoo et al. 2017).

Geometric models of transportation networks such as road spacings or densities have been used to identify optimal design criteria. In order to plan the ideal forest road network, important role can play both the optimal road density and the optimal length (Heinimann 1998; Matthews 1942). Hence, the cost of wood transportation and the construction of forest roads should be balanced with the existence of a suitable forest road network that gives access to the forest, and at the same time to have the minimum possible length and the optimum road density and road spacing (Heinimann 2017; Kroth 1973; Matthews 1939; Olsson 2004; Olsson and Lohmander 2005; Segebade 1964; Soom 1952; Sundberg 1963; Tan 1992).

In order to achieve the above goal, the recommended technique, which is presented in this paper, can be applied. More particularly, we estimated the forest roads' total construction cost, the annual maintenance cost, and the skidding cost. Admittedly, the construction of forest roads destroys the forest ecosystems. So, in the forest roads construction cost assessment, we took under consideration the evaluation of the total economic value of forest goods and services that are lost from forest roads' construction (Albanis et al. 2015; Budge et al. 2011; Costanza et al. 1997; Croitoru 2007a, 2007b; Mantau et al. 2007; Merlo and Croitoru 2005; Meyer et al. 2012; TEEB 2010). Finally, the optimum eco-efficient and economical forest roads densities are determined based on the IRR method. This method refers to productive forests and we take under consideration the values of the national forestry characteristics and the national regulations.

Materials and methods

On the orientation map (Fig. 1), the research area is presented. As research area, management units 3 and 4 (Fig. 2) of the community forest, which is 18 km away from Metsovo town in the North of Pindos Mountains,

have been chosen. Specifically, it is located at 21° 05' 89" and 21° 10' 5" Northern Latitude and between 39° 82' 34" and 39° 85' 49" Western Longitude and it is about 580 ha. These forest management units present the typical Greek mountainous forest units characteristics (natural mixed forests, low harvesting volume, selective logging, steep terrain, high and coppice forest management form); forest age is group-selective forest (coniferous) even aged forest (mixed) and even aged forest (broad-leaved) and tree height. In addition, these units are the most productive management units of Metsovo forest, according to the local Forest Service.

For the needs of the research we used the following: the ArcGIS software, digital orthophotomaps of the area and respective Digital Elevation Models, DEM. In addition, we digitized the land uses and the forest road networks. According to the Hellenic National Regulations there are three categories of forest roads A, B, and C (A access roads, B main forest roads, and C secondary). We also used the forest management plan of Forest Service for the municipality of Metsovo (management units 3 and 4) for the years 2015–2024. According to this management plan, the average timber harvesting volume is 1.86m³/ha/year. The forest productivity includes not only *Pinus nigra* but also *Fagus sp.* Also, according to the forest management plan, *Pinus leucodermis* is not taken under consideration in forest productivity.

2.1 Internal Rate of Return Method

The recommended method is an approach that includes the evaluation lifecycle costs of forest roads which is combined with the IRR method through linear equations.

The IRR method can be used to evaluate the attractiveness of an investment. The IRR is a profitability metric used by investment managers to determine which investments are likely to yield the greatest return per capital investment. According to this method, we are searching for the discount rate at which the present value of all future cash flow is equal to the initial investment or, in other words the IRR is the interest rate, also called the discount rate that is required to bring the net present value (NPV) to zero. That is the interest rate that would result in the present value of the capital investment, or cash outflow, being equal to

the value of the total returns over time, or cash inflow. The capital investments in forest roads construction can be written as:

$$NPV = \sum_{t=1}^T \frac{C_t}{(1+r)^t} - C_0 = 0$$

or $It-C_0 = 0$

or analytically $It-C_0 = \left(\sum_{t=1}^N \frac{e}{(1.0P)^t} + \frac{LN}{(1.0P)^N} \right) - \left(KD + \sum_{t=1}^N \frac{SU}{(1.0P)^t} \right) = 0$

where

- I_t the total future cash inflows
- C_0 the total initial investment costs (cash outflows)
- t the time
- N the time period of capital depreciation (years)
- e the net cash inflows during the period t
- P the discount rate %
- LN the liquidation charges (=residual value)
- KD the forest roads construction cost
- SU the forest roads annual maintenance cost

An investment is considered acceptable if its internal rate of return is greater or equal than established minimum acceptable rate of return or cost of capital. Hence, the project is considered acceptable, otherwise the project is rejected.

At the forest operations planning, the value of the road density D is significantly influenced by the costs that are required for both construction and maintenance of roads, as well as for both skidding and the loss of land annuity (Kroth 1973; Matthews 1939; Soom 1952; Segebaden 1964; Sundberg 1953; 1963), as given below:

Cash outflows (negative impacts from forest roads construction)

Land annuity, K_B

The construction of forest roads destroys the productive forest ecosystem land. This area is known as “Right of Way” and is equal to the deck construction width as well as the forest roads hillslopes width (Ryan et al. 2004). The loss of land annuity that is derived from the catastrophe of the productive forest land is calculated from the equation:

$$K_B = \frac{b \cdot B \cdot 0.0p^*}{N} D, \tag{1}$$

where

K_B the land annuity (euro/m)

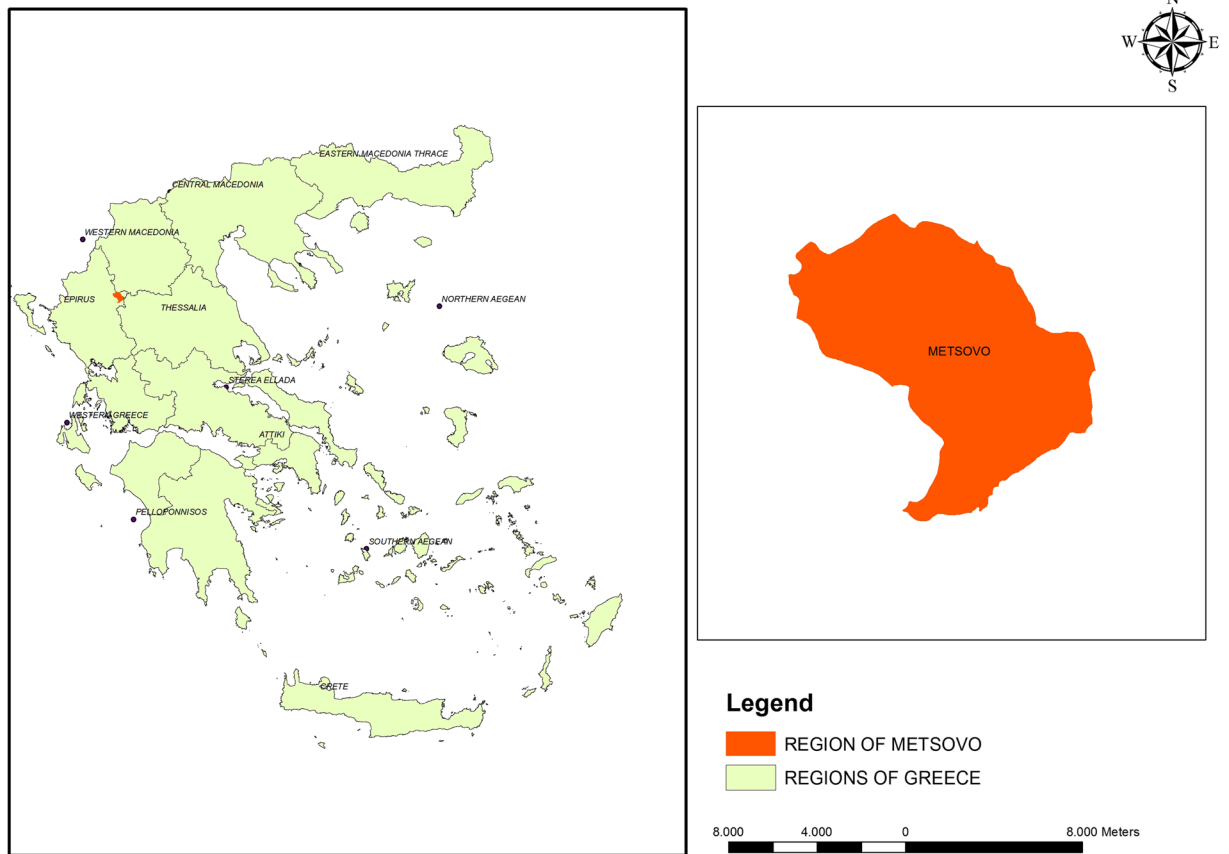


Fig. 1 Location of the study area, municipality of Metsovo

- b* the width of forest road tree clearance
- B* the land value (euro/m²)
- p* the discount rate
- N* the annual timber harvesting volume
- D* the forest road density

Based on the Hellenic forestry characteristics and the predominant economic situation, the appropriate discount rate is 3.5% (Albanis et al. 2015).

The construction of each forest road causes the reduction of the productive forest ecosystem land. This decrease is mainly dependent on the width of the “Right of Way.”

For the assessment of the annual economic value of the forest ecosystem land, (a) the values of forest ecosystem goods and services and (b) the negative values (negative externalities) were separately estimated and subsequently summed algebraically. Afterwards, the model estimates the total forest ecosystem evaluation by dividing the annual

economic value with the discount rate, i.e., capitalize the annual forest ecosystem value (use the capitalization formula sustainable annuity). So, the total economic value of the forest is expressed by the following equation (Albanis et al. 2015):

Total annual forest ecosystem value evaluation = (annual values of forest ecosystems goods and services – annual negative values)/discount rate. We shall write the above expression as:

$$TEV = \frac{[(Vw + Vnwfp + Vg + Vh + Vr + Vps + Vsq + Vb) - (Df + De)]}{p} \tag{2}$$

where

- TEV total economic forest ecosystem value evaluation
- Vw the annual value of wood production
- Vnwfp the value of non-wood forest products
- Vg the annual grazing land value
- Vh the annual hunting value

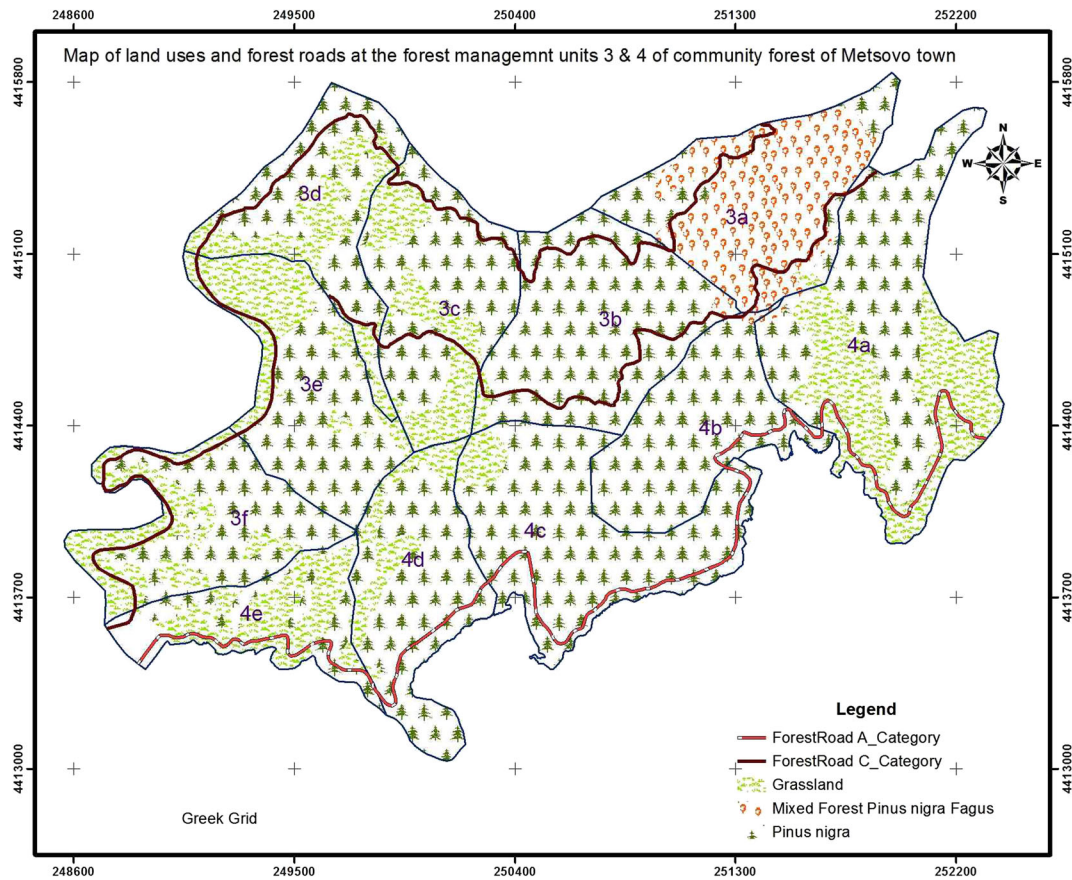


Fig. 2 Land uses and forest roads of the study area, forest of Metsovo town

- Vr the annual recreational value
- Vps the annual value of forest land protection (i.e., degradation)
- Vsq the annual value of carbon sequestration
- Vb the annual value of forest biodiversity
- Df the annual loss from wildfire danger
- De the annual forest land loss due to the degradation
- p the discount rate (%)

All values are expressed in currency units (euro).

Capital depreciation and interest rate which has been invested for the forest road construction, K_R

The annual interest of construction costs that depends on the road density and the annual timber production is calculated by the equation:

$$K_R = \frac{A * 1.0p^n * 0.0p * D}{N (1.0p^n - 1)} \tag{3}$$

where

- K_R the annual interest of construction costs
- A the forest road construction cost (euro/m)
- D the road density (m/ha)
- n the duration for the capital depreciation that is needed for the construction of forest roads
- p the discount rate
- N the annual timber harvesting volume (m³/ha)

The time period for the capital depreciation that is needed for the construction of forest roads is for the Greek forestry conditions according to the Hellenic National Forestry characteristics, $n = 30$ years.

Annual maintenance costs, K_{SU}

The required costs for the annual maintenance of forest roads that charge each cubic meter of timber produced in forest complex are calculated by the equation below:

$$K_{SU} = \frac{Su^*}{N} D, \quad (4)$$

where

Su the annual maintenance costs (€/m)
 N the annual timber harvesting volume (m³/ha)

Cash inflows (positive impacts from forest roads construction)

Skidding costs, K_r

In order to calculate the timber skidding costs, we applied the following equation which is valid for the one side skidding (the skidding in research area is one side based on the field observations and the forest service recommendations) since the calculation of the skidding costs is according to its length:

$$K_r = Cf + Cv^*REt = Cf + Cv^* \frac{5000^*}{D} F^*W, \quad (5)$$

where

Cf the fixed skidding costs
 Cv the variable skidding costs
 REt the real skidding distance
 F the average skidding distance fixing coefficient for the research area
 W the average forest road fixing coefficient for the research area

The fixed skidding cost Cf is independent of the skidding distance and depends on the transportation of harvesting equipment in logging regions, the pre-harvesting operations, the skidding logs, the logs loading onto trucks, the barriers removal, and the yarding or skidding logs to a central location as well as the bucking at the collection center.

The variable skidding cost Cv depends on the average skidding distance REt and is affected by the ground and climatic characteristics, the timber harvesting volume (m³/ha), the log dimensions, the skidding means

and method, the loan volume, the skidder, hauling draught animals and machines productivity, and the skidding planning.

The average forest road fixing coefficient for the research area W is the ratio of the actual forest road length to their segment line length. This coefficient is affected by the ground topography.

The average skidding distance fixing coefficient for the research area F is affected by the ground slope. It is also affected by the average skidding distance and the length of forest roads.

The forest road density gets the economic optimum rate when the annual inflows from the forest roads (skidding costs K_r) are becoming equal to the total outflows (forest road construction and maintenance costs K_w) and according to IRR method. This rate is called as the economic optimum forest road density.

$$K_w = K_r \quad (6)$$

The forest road density gets the eco-efficient optimum rate when the total costs (K_s) of forest road construction and maintenance (K_w) along with the skidding costs (K_r) get the minimum rate. This rate is called as the eco-efficient optimum forest road density.

$$K_s = K_w + K_r = \text{minimum} \quad (7)$$

Results

Land annuity evaluation, K_B

In the study area, the Forest Service of Metsovo classifies the forest roads according to their usage into categories A and C. The total length of category A is 6294.04 m and the total length of category C is 10,125.38 m. (Table 1). Hence, the total length of forest roads that cross units 3 and 4 equals to 16,419.42 m. As a consequence, the existing forest road density is $Dex = \text{total length of forest roads}/\text{total research area} = 16,419.42/580 = 28.31 \text{ m/ha}$.

Accordingly, we calculated the average width of forest road tree clearance b , which is 16.65 m for category A (6294.04 m) and 10.33 m for category C (10,125.38 m).

Table 1 Linear equations for the skidding cost of the coniferous and the deciduous species related to the skidding distance x

Wood category	Distance (m)	<i>Pinus nigra</i>	<i>Fagus sp.</i>
Log for timber (euro/m ³)	$x \leq 500$	$4.12 + 1.49x^{**}$	$4.43 + 0.73x^{**}$
Fuelwood (euro/wood volume with empty spaces)	$x \leq 500$	$2.73 + 1.05x^{**}$	$3.62 + 1.05x^{**}$

Source: (FEK Issue B’/142/28-1-2014)

**The skidding distance in hectometers

$$So, b = \frac{6294.04}{16419.42} * 16.65 + \frac{10125.38}{16419.42} * 10.33 = 12.73m$$

From Eq. (1), replacing the numbers we have:

$$K_B = \frac{12.73 * 0.9 * 0.035}{1.86} D = 0.22D, \tag{8}$$

where

- b 12.73 m
- B 0.9 euro/m² (Albanis et al. 2015)
- p 3.5%
- N 1.86 m³/ha/year

Capital depreciation and interest rate which has been invested for the forest road construction, K_R

Based on the Forest Service of Metsovo, the forest road construction cost for category A is 135.64 €/m. and for category C is 10.89 €/m.

Hence, the rate for the forest road construction cost is:

$$A = \frac{6294.04}{16419.42} * 135.64 + \frac{10125.38}{16419.42} * 10.89 = 51.51 + 6.75 = 58.29€/m$$

The annual interest of construction costs (from Eq. (3) replacing the numbers) is expressed as:

$$K_R = \frac{52.89 * 1.035^{30} * 0.035^*}{1.86 * (1.035^{30} - 1)} D = 1.7D, \tag{9}$$

where

- n 30, the duration for the capital depreciation that is needed for the construction of forest roads

Annual maintenance costs, K_{SU}

As reported by the Forest Service of Metsovo, the annual forest road maintenance cost is $Su = 0.42$ €/m.

From () we calculate:

$$K_{SU} = \frac{Su^*}{N} D = 0.23D \tag{10}$$

Skidding costs, K_r

Due to the fact that the research area’s forest is non-industrial which is managed not only for wood production, the fixed skidding costs C_f and the variable skidding costs C_v for the research area are accounted based on the Hellenic National Regulations and the Timber Assignment Prices for the year 2014, (FEK Issue B’/142/28-1-2014). Consequently, the linear equations for the skidding cost of the coniferous and the deciduous species related to the distance x ($x \leq 500$ m, the average skidding distance according to the local forest service is approximately 146.76 m) are given in the table below.

In units 3 and 4 of the research area, we evaluated that the forest species synthesis contains 96.72% coniferous (*Pinus nigra*) and 3.28% deciduous (*Fagus sp.*) as well as the logging timber synthesis contains 82% timber and 18% fuelwood.

a) Fixed skidding costs

1. Timber 82%

$$Cf_1 = 0.82(0.9672 \times 4.12 + 0.0328 \times 4.43) = 3.38 m^3 \tag{11}$$

2. Fuelwood 18%

$$Cf_2 = 0.18(0.9672 \times 2.73 + 0.0328 \times 3.62) \times 1.49 = 0.74 m^3 \tag{12}$$

(1.49 transformation coefficient of *Fagus sp.* wood volume with empty spaces in m³)

It was estimated that at the research area the total fixed skidding costs are as follows:

$$Cf = Cf1 + Cf2 = 3.38 + 0.74 = 4.12 m^3 \tag{13}$$

b) Variable skidding costs

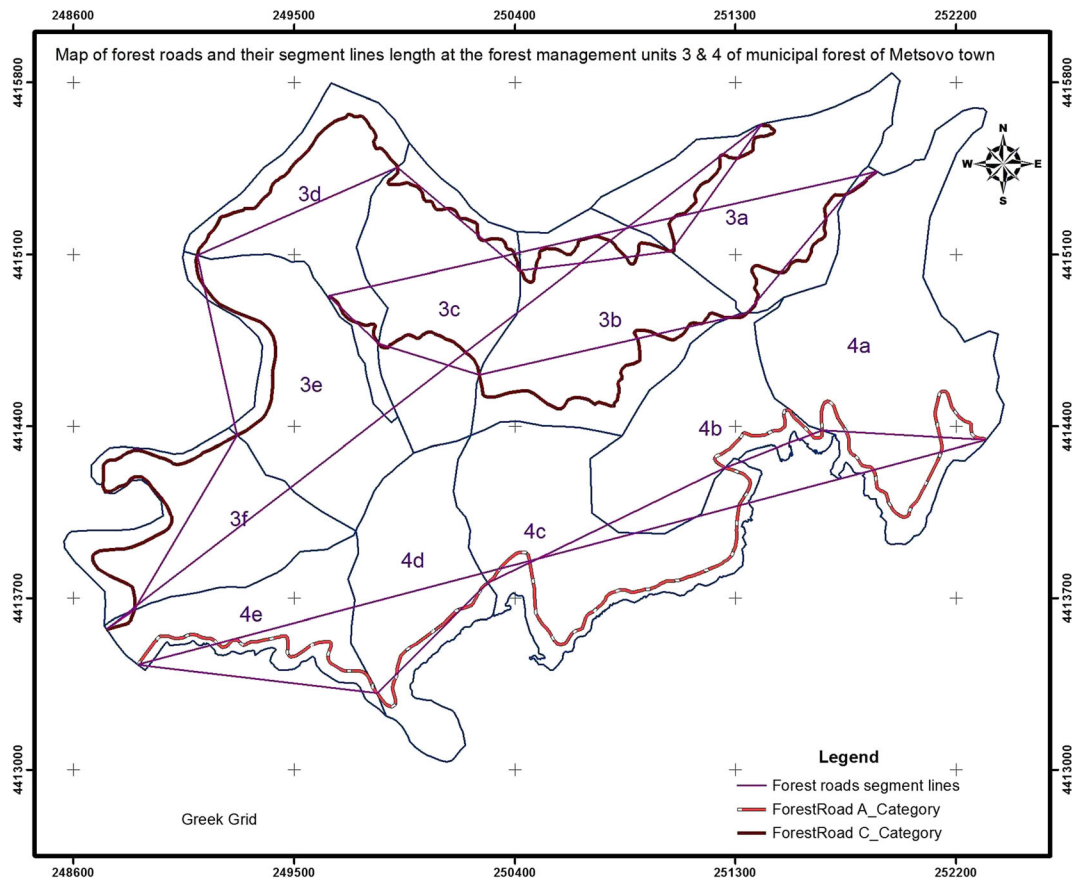


Fig. 3 Map of the average forest road fixing coefficient W evaluation

1. Timber 82%

$$Cv_1 = 0.82(0.9672 \times 1.49 + 0.0328 \times 0.73) = 1.20 \text{ m}^3 \quad (14)$$

2. Fuelwood 18%

$$Cv_2 = 0.18(0.9672 \times 0.98 + 0.0328 \times 0.98)1.49 = 0.28 \text{ m}^3 \quad (15)$$

(1.49 transformation coefficient of *Fagus* sp. wood volume with empty spaces in m^3)

From Eqs. (Epstein et al., 1999) and (Epstein et al., 2007), we estimated that at the research area the total variable skidding costs are as follows:

$$Cv = Cv_1 + Cv_2 = 1.20 + 0.28 = 1.48 \text{ m}^3 \quad (16)$$

From Eqs. (Dietz et al., 1984) and (Epstein et al., 2006), we estimated that the total skidding cost for units 3 and 4 is:

$$Kr = 4.12 + 1.48 \times REt \text{ €/m}^3 \quad (17)$$

We can now proceed to the final skidding costs equation, if in Eq. (Epstein et al., 2001) we add 10% increment due to hillslope (steep terrain, average hillslope 35–70%) as well as 10% increment due to the forest market distance from logging area (≤ 50 km) (Metsovo Forest Worker Cooperatives).

$$1.2 \times (4.12 + 1.48) = 4.94 + 1.78 \times REt \text{ €/m}^3 \quad (18)$$

Fixed skidding costs: 4.94 €/m³

Variable skidding costs:

$$\frac{1.78^*}{100} REt = 0.0178 REt \text{ €/m}^3 \quad (19)$$

For the evaluation of the average forest road fixing coefficient, W for the research area ModelBuilder tool of ArcGIS has been used. Hence, the map (Fig. 3) has been created and the rate of W has been estimated to 1.504.

Table 2 Estimation of the average forest road fixing coefficient W

a/	Forest unit	Forest stand	Area (ha)	Forest roads lengths			Segment line length (m)	Existing forest road density (m/ha)	Forest road fixing coefficient W	Coefficient average rates		
				A category (m)	C category (m)	Forest road length (m)				W ₁	W ₂	Average forest road fixing coefficient W
1	2	3	4	5	6	7	8	9 = (7)/Σ(4)	10 = (7)/(8)	11 = Σ(10)/n	12 = Σ[(7) × (10)]/Σ(7)	13 = Σ[(11) + (12)]/2
1	3	a	58,00	-	858,29	858,29	637,56	1346	1155,44			
2	3	b	61,00	-	824,93	824,93	630,58	1308	1079,18			
3	3	c	61,00	-	898,77	898,77	620,14	1449	1302,59			
4	3	d	52,00	-	1493,08	1493,08	1043,92	1430	2135,50			
5	3	e	52,00	-	841,88	841,88	655,83	1284	1080,71			
6	3	f	44,00	-	527,28	527,28	431,33	1222	644,57			
7	3	a	47,00	-	1222,51	1222,51	892,52	1370	1674,51			
8	3	b	47,00	-	324,87	324,87	281,60	1154	374,79			
9	3	c	50,00	-	962,33	962,33	751,52	1281	1232,27			
10	3	d	47,00	-	1783,44	1783,44	827,08	2156	3845,65			
11	3	e	86,00	1603,95	-	1603,95	669,93	2394	3840,19			
12	3	f	86,00	1603,95	-	1603,95	669,93	2394	3840,19			
13	3	a	42,00	693,42	-	693,42	422,60	1641	1137,79			
14	3	b	42,00	693,42	-	693,42	422,60	1641	1137,79			
15	3	c	63,00	1904,52	-	1904,52	1077,70	1767	3365,68			
16	3	d	45,00	778,19	-	778,19	637,21	1221	950,36			
17	3	e	32,00	150,16	150,16	150,16	136,85	1097	164,76			
18	3	f	32,00	150,16	150,16	150,16	136,85	1097	164,76			
Sum			580,00	6294,04	10125,38	16419,42	10887,02	28,31	25,577	1,421	1,588	1,504
Average												

The table below shows the estimation of average forest road fixing coefficient W .

The average skidding distance fixing coefficient F for the research area according to the local Forest Service has been estimated to 2.41.

Eventually, we obtain from Eq. (Albanis et al., 2015):

$$K_r = 4.94 + 0.0178 \times \frac{5000}{D} \times 2.41 \times 1.504$$

$$= 4.94 + 0.0178 \times \frac{18123.2}{D} = 4.94 + \frac{322.6}{D}, (20)$$

Correspondingly, according to Eq. (Forsyth et al., 2006), the rate of the actual skidding distance REt is given in relation to the road density D from the relationship below:

$$REt = \frac{18123.2}{D} (21)$$

We mathematically expressed the total construction cost in relation to the road density D :

$$K_W = (K_B + K_R) + K_{SU} = 0.22D + 1.7D + 0.23D = 2.15D (22)$$

Economical and eco-efficient optimum forest road densities evaluation

From Eqs. (Bont, 2012), (Forsyth et al., 2006), and (Geneletti, 2003) derives that the economical optimum forest road density evaluation occurs when the skidding costs K_r are equal to the total forest road construction and maintenance costs K_W , where in our case they are mathematically expressed in relation to the road density D :

$$2.15 * D = 4.94 + \frac{322.6}{D} (23)$$

We can now proceed to the calculation of Eq. (23) where, $D_{\text{economical}} = 13.45$ m/ha, whose rate is smaller than $D_{\text{ex}} = 28.31$ m/ha.

As mentioned above, from Eq. (Boston, 2016), the eco-efficient forest road density evaluation occurs when the total K_s forest road construction and maintenance costs K_W along with the log skidding costs K_r get the

Table 3 Total cash outflows and inflows for the research area

Total initial investment costs (cash outflows)		Total future cash inflows		Total (Ks) forest road construction and maintenance along with the skidding costs K_r
Land annuity	Capital depreciation and interest rate which has been invested for the forest road construction	Annual maintenance costs	Forest road construction along with maintenance costs	
$K_B = 0.22D$	$K_R = 1.7D$	$K_{Su} = 0.23D$	Fixed skidding costs	
			Variable skidding costs	
			$K_r = Cf + Cv + Cv = 4.94 + (322.6/D)$	$K_s = K_w + K_r = 2.15D + 4.94 + (322.6/D)$
			$K_w = K_B + K_R + K_{Su} = 2.15D$	

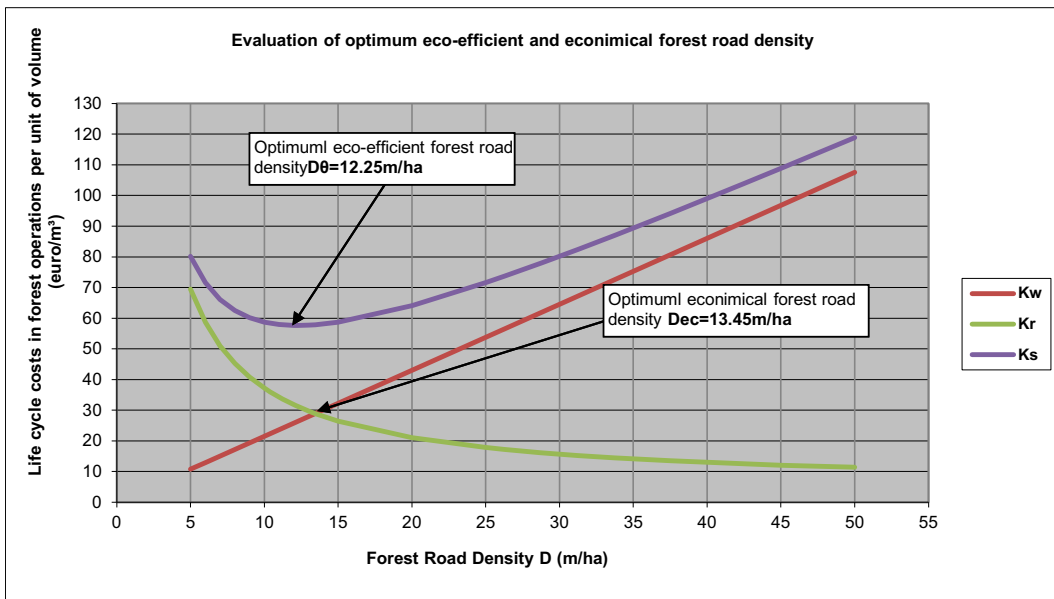


Fig. 4 Graph of eco-efficient and economical optimum forest road densities evaluation in function to forest operations life cycle costs [forest road construction along with maintenance costs (Kw), skidding costs (Kr), and total costs (Ks)]

minimum rate, where in our case they are mathematically expressed in relation to the road density D :

$$K_s = 2.15D + 4.94 + \frac{322.6}{D} = \text{minimum.} \quad (24)$$

$$\frac{dK_s}{dD} = 0 \quad (25)$$

$$\text{or } 2.15 - \frac{322.6}{D^2} = 0 \quad (26)$$

The above equation is valid when the derivative of Eq. (Gumus, 2009) is equal to zero:

$$\text{or } D^2 = \frac{322.6}{2.15} = 0$$

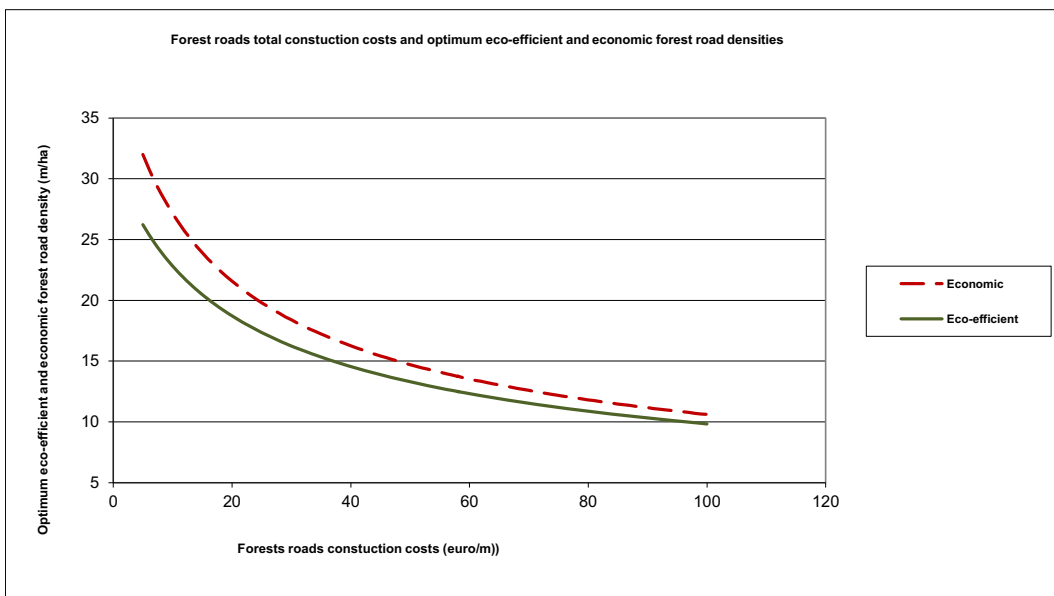


Fig. 5 Optimum economical and eco-efficient road densities in relation to the total construction costs of forest roads

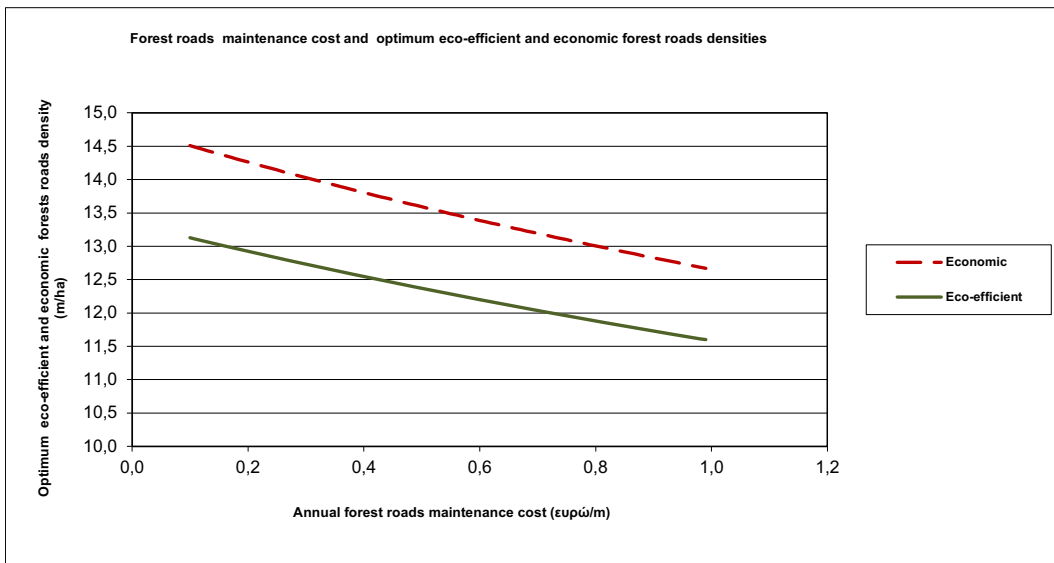


Fig. 6 Optimum economical and eco-efficient road densities in relation to the annual forest road maintenance cost

or $D_{eco-efficient} = 12.25$ m/ha, whose rate is smaller than $Dex = 28.31$ m/ha (Table 2).

Table 3 shows the research area results (inflows and outflows equations) and Fig. 4 presents the graph form of the eco-efficient and economical optimum forest road densities evaluation. When the graphic curve of the skidding cost K_r intersects the graphic curve of the total costs (K_w) of construction ($K_B + K_R$) along with the total maintenance costs K_{su} of forest roads, then the intersection represents the economical optimum forest road density. Furthermore, the minimum rate of the graphic curve of the total (K_s) forest road construction and maintenance along with the skidding costs K_r represents the eco-efficient optimum forest road density.

Figure 5 illustrates the diagram that represents the optimum economical and eco-efficient road densities in relation to the total forest road construction cost. In addition, Fig. 6 presents the graph of optimum economical and eco-efficient road densities in relation to the annual forest road maintenance cost. Finally, Fig. 7 shows the diagram of the optimum economical and eco-efficient road densities in relation to the log skidding cost.

Due to the fact that $Dex > D_{economical}$, we can understand that the total length of the constructed forest road networks is greater than the forest roads length of what the research area actually needs.

In addition, the forest road network in this area was not eco-efficient friendly planned since the construction

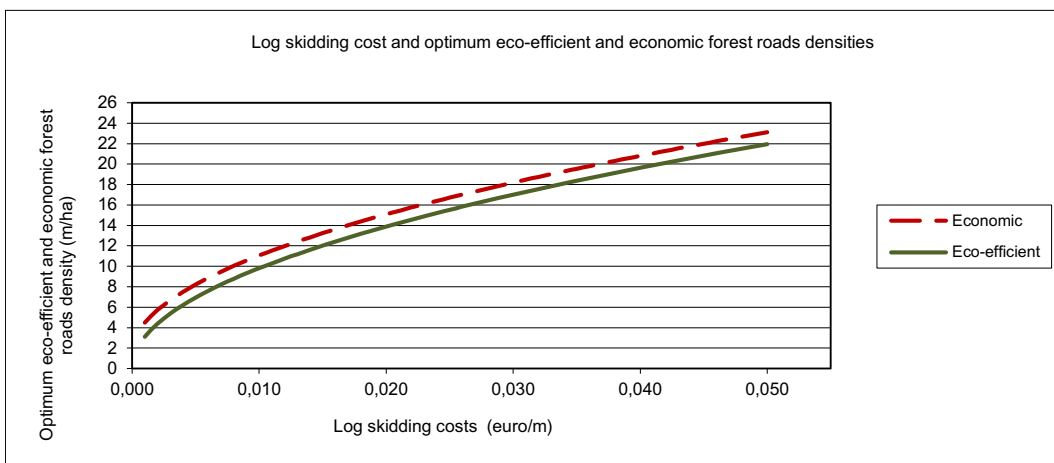


Fig. 7 Optimum economical and eco-efficient road densities in relation to the log skidding cost

of forest roads caused the reduction of the productive forest ecosystem land. This reduce depends on the technical road characteristics (forest road tree clearance and the deck construction width, as well as the forest roads hillslopes width).

The results show that the rate of the optimum eco-efficient road density ($D_{\text{eco-efficient}} = 12.25$ m/ha) is very close to the rate of the optimum economical road density ($D_{\text{economical}} = 13.45$ m/ha). Therefore, it is obvious that the most eco-friendly approach to plan and finally to construct forest transportation systems is at the same time the most economically efficient.

Conclusions

Through the application of this method, decision makers can improve the sustainable management in forestry. The conclusions that derive from the above are based on values that constitute the basis of the eco-friendly and economically efficient and feasible evaluation of the forest roads construction and planning. Hence, this method plays a crucial role in the optimum solution selection (financial and environmental aspect) for the planning and finally the construction of forest road network layout.

In this technique, we used the life cycle costs based on the IRR method and we assessed the optimum eco-efficient and economical forest roads densities with linear equations. Also, we presented the method graphically. Consequently, it is effective to evaluate the attractiveness of the forest roads as an investment from two aspects, (a) economical and (b) environmental. At the forest roads' lifecycle costs, we took into account the (a) total construction costs, (b) annual maintenance cost, and c) log skidding cost. Moreover, at the assessment of the forest roads construction, we estimated the total economic value of forest goods and services that are lost from the roads' construction. So, we estimated not only the forest road networks lifecycle costs but also their ecological footprint.

Furthermore, this approach is considered to be reliable not only for the evaluation of the constructed forest roads but also for the study of their impacts to the environment before the construction of new ones. Thus, the application of an holistic evaluation method for the forest road networks layout and transportation systems in mountainous regions must be based on the principles of the multi-functional sustainable development that

depend on the eco-efficient utilization of the natural resources. Moreover, it is very important that the sustainable development to be based on the activation of the human and social resources and the management of the unique cultural as well as the financial characteristics that each region offers. For the achievement of the above, major role plays the recommended technique.

Summarizing, we would like to emphasize that the future bio-economy in the local and national level will be strengthened, as long as the recommended tool will be applied by the decision makers and forest managers. This will be achievable if the policy makers will rely on eco-efficient sound, physically feasible, and economically efficient parameters.

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