Qualitative evaluation and optimization of forest road network to minimize total costs and environmental impacts

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An efficient and low-cost transportation network is necessary for sustainable management. Roading and log skidding are the most expensive and destructive operations in forest environment, unless carefully planned and evaluated. A transportation network has to be assessed and optimized to minimize the total cost of road construction and its environmental impact. The aim of this study was determining the optimum forest road network density, and evaluating the quantity and quality of the existing forest road network. In order to determine the optimum forest road network density, skidding cost, road construction and maintenance costs, and harvesting volume in each compartment were considered. Then optimum skidding distance was calculated with regard to optimum road density and total correction factors. The relative openness and efficiency coefficient of the existing forest road network were determined for the calculated optimum skidding distance, using ArcGIS. The results showed that the optimum road density, relative openness and road network efficiency coefficient were 21.5 m ha^{-1}, 90% and 32%, respectively. As a result, when the quality of a forest road network has to be evaluated, road network efficiency coefficient is more efficient than relative openness, that *per se* cannot be considered as an appropriate indicator.

Keywords: Forest road network, Environmental impact, Qualitative evaluation, Optimum road density, Efficiency coefficient, GIS

Introduction

Forests support a lot of ecosystem services, including primary products, secondary products, water supply, hydrological regulation, environmental purification, soil formation, soil conservation, biodiversity conservation, recreation, etc. (Gios & Clauser 2009, Gaodi et al. 2010). One of the main objectives of forest management is the sustainable utilization of natural resources (Mataji et al. 2010). Forest road planning plays an important role in forest management and logging practices. Roads are essential structures to provide access to the forest for wood production and logging (Abdi et al. 2009). On the other hand, road construction and log skidding are the most expensive and destructive operations in the forest environment, leading to soil compaction and increasing surface runoff and soil erosion along the skidding path. Therefore, the viability and profitability of operational forest management plans are deeply influenced by road construction and maintenance costs, as well as the road network structure (Kirby et al. 1986). A large area of forest is destroyed during road construction, provoking not only economic losses, but also changes in the environmental conditions (Jadczyk 2009). Road construction in forest may also cause biodiversity loss as a result of habitat fragmentation (Hui et al. 2003, Smulders et al. 2009, Da Silva et al. 2010), making forest communities more prone to impoverishment and depletion. As the high density of forest road network will lead to the excessive economical and environmental costs, forest road managers have to carefully evaluate and optimize the forest road network density for minimizing the total costs and environmental impacts of these infrastructures. Average log skidding distance is an important component to evaluate the quality of forest road network, and should be considered for computing the optimal forest road network density (Zhixian & Zhili 1997).

Matthews (1942) was the first who developed a two dimensional model for skidding distance, with assumptions of flat terrain condition, regular road distribution, and provided that logs are carried out on the shortest path to the nearest road. Segebaden (1964) improved the road spacing model by introducing network and transport correction factors. Heinimann (1997) reported that the above mentioned assumptions do not apply in mountainous conditions with sloped terrain, and introduced a slope correction factor to compute the real skidding distance.

Road technical specifications and wood extraction methods are two main factors affecting optimum road spacing and density, aimed to minimize the total cost of roading and skidding (Rowan 1976, Naghdi & Mohammadi Limai 2009). Moreover, the timber volume to be harvested is an important factor affecting the quantity and quality of forest road network density. Sedlak (1983) calculated road spacing with regard to volume of annual growth and reported lower average road spacing in parts of forest with higher annual growth and larger harvesting volume.

There are many researches aimed to determine road and skidding costs, road spacing and generally optimal road network under different logging practices (Lihai et al. 1996, Tan 1999, Tucek & Pacola 1999, Chung & Sessions 2001, Heralt 2002, Demir & Tolga 2004, Anderson & Nelson 2004, Aruga 2005, Pentek et al. 2005, Najafi et al. 2008).

Chung & Sessions (2001) introduced the Network 2001 program for the analysis and selection of optimum forest road network. Pentek et al. (2005) used forest road relative openness and efficiency coefficient to analysis forest road network with determination of optimum road density and average skidding distance.

In the Caspian forests, most of harvested timbers are extracted by ground-based skidding system. In that context, optimal average skidding distance must be determined as first step in order to get the optimum forest road network density. However, Caspian forests are mainly located in mountainous area, where studies based on the theoretical skidding distance (namely, those based on Matthews's model) do not apply.

The present study aimed to evaluate the quantity and quality of the existing forest road network, with estimation of optimum road density and road network efficiency coefficient in ArcGIS, with respect to road construction, maintenance and skidding cost, and harvest volume in Namkhaneh district, Kheyroud Educational and Research Forest, northern Iran.

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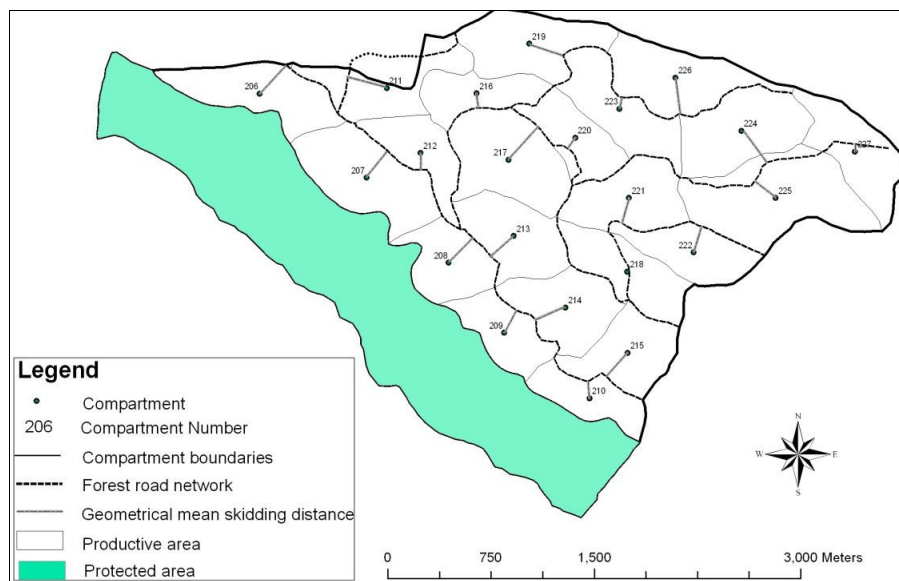
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Fig. 1 - Defined geometrical mean skidding distance in each compartment.

Material and methods

Study site

The temperate deciduous forests of northern Iran, known as the Caspian forests, cover an area of around 2 million hectares, ranging from the level of the Caspian Sea up to 2200 m a.s.l. Oriental beech (*Fagus orientalis* Lipsky) is the most important broadleaved deciduous species in the Caspian region, forming natural pure and mixed forests (Ahmadi et al. 2009). The study site is located in Nowshahr (latitude: 36°33' N, longitude: 50°33' E). The research was carried out on road network of Namkhaneh district, which covers 1083 ha, ranging from 350 to 1350 m a.s.l.; slope varies between 0 to 80%. Only 788 ha of the district area are considered as harvesting area, while the rest (295 ha) were excluded as protected area. The management in the district is mixed un-even aged high forest, with single and group selective cutting regime. Forest roads are categorized as permanently main forest roads used for trucking, with an average width 6.5 m and longitudinal slope 3 to 8% (Majnounian et al. 2010). Overall raod length is 15.8 km and current forest road density is 20 m ha⁻¹. Ground skidding using wheeled cable skidders (Timber Jack 450C, 174 hp and 12 tn) is the most common method of wood extraction in this mountainous, uneven aged hardwood forest. Cable systems are not available and not used in the Caspian forest.

Determination of the average real means skidding distance

In order to determine average real means skidding distance, the center of gravity of each compartment was defined, and its distance to the nearest road was measured in an ArcGIS environment. Indeed, this distance is the geometrical mean skidding distance for each compartment (Fig. 1), which has to be multiplied by the network correction factor to obtain the real mean skidding distance (Tab. 1). To obtain the average real means skidding distance at the district level, averages were weighted on the log volume to be harvested in each compartment.

Optimum forest road network density estimation and comparison with the existing density

The optimum forest road network density was calculated using the following equation (Rebula 1981) that consider road construction, maintenance, skidding costs and harvesting volume (eqn. 1):

$$D_O = 100 \cdot \sqrt{\frac{E \cdot T_p \cdot F \cdot K_s}{T_A \cdot T_o - d_s E}}$$

where D_O is the optimum forest road network density (m ha⁻¹), E is the average annual quantity of extracted log (m³ ha⁻¹); T_P is the cost of skidding 1 m³ of log at the distance of 1 m (US$ m⁻³ m⁻¹); F is the walking cost factor, that Rebula (1981) estimated as 51.7% of skidding cost per skidder (see below); K_S is the overall correction factor of the theoretical mean skidding distance; T_A is the average annual amortization of 1 m of forest road (US$ m⁻¹); T_O is the average annual maintenance cost of 1m of forest road (US$ m⁻¹); d_S is the secondary profit from the forest road network (US$ m⁻³). Depending on the region considered, this parameter may include profits from mushrooms, resins, ornamental seeds and pods, aromatic plants or plants for pharmaceutical products, and other non-wood forest products. As wood harvesting is the main and the only profit in the study area, this parameter was not taken into account in our estimation.

To obtain the value for the walking cost factor F in eqn. 1, several parameters need to be preliminarily defined, such as the number of workers, the average walking speed, the payment of workers per hour, the intensity of

Tab. 1 - Harvesting volume, SD_{EG} (existing geometrical mean skidding distance) and SD_{ER} (existing real mean skidding distance) of each compartment in the study area.

Compartment	Area (ha)	Harvesting volume (m³)	SD_{EG} (m)	SD_{ER} (m)
206	39.9	297.5	271.1	428.3
207	49.7	178.5	233.6	369.1
208	29.3	195.5	243.2	384.3
209	26.2	246.5	176.7	279.2
210	23.6	85	120.7	190.7
211	31.1	238	284.9	450.1
212	25.4	170	108.7	171.8
213	35.3	212.5	209.2	330.5
214	35.6	246.5	222.6	351.7
215	32.2	221	219	346
216	24	59.7	93	146.9
217	48.6	238	308.4	487.3
218	34.1	119.2	12.7	20.1
219	40	347.8	245	387.1
220	26.5	212.5	85	134.4
221	35.6	297.5	175.2	276.8
222	28.6	103	187.7	296.5
223	35.2	246.5	82.1	129.7
224	44	255	244.1	385.7
225	66.1	261	186.8	295.1
226	41.3	314.5	253	399.6
227	35.3	212.5	55	86.6

work. Considering the wheeled skidder used in the study area and the topographic conditions in this study, fairly similar to those previously reported in the literature (Rebula 1981, Pentek et al. 2005), the value of 51.7% was used.

Average optimum geometrical mean skidding distance

In order to calculate the average optimum geometrical mean skidding distance, the following equation was used (eqn. 2):

$$Sd_{OR} = \frac{K_s}{D_o} \cdot 10000$$

where Sd_{OR} is the average optimum real means skidding distance, D_O and K_S were already defined above.

Dividing th Sd_{OR} by network correction factor (K_G), the average optimum geometrical mean skidding distance may be obtained (eqn. 3):

$$Sd_{OG} = \frac{Sd_{OR}}{K_G}$$

Determination of the forest road relative openness

Buffer zones wrapping the existing roads on both sides and extending twice the optimum average geometrical mean skidding distance were created in the ArcGIS environment (Fig. 2). Indeed, the buffer zone represents the maximum skidding distance. Then, the relative openness was calculated using the following equation (eqn. 4):

$$O_R\% = \frac{O_E}{A_T} \cdot 100$$

where O_R is the relative openness of forest road, A_T is the total area of the district (ha) and O_E is the effective opening-up area (ha). The buffer opening-up zone falling outside the district area and the overlapped buffer opening-up were excluded from this analysis.

Evaluation of the forest road network efficiency coefficient

Opening-up effectiveness indicates the effectiveness of the forest road location. In the presence of a regular road network, the effective opening-up would be at the maximum level with regard to road density. However, an ideally distributed road network does not occur in practice (Hruza 2003). In order to calculate the forest road network efficiency coefficient, the following equation was used (eqn. 5):

$$K_U\% = \left[1 - \frac{O_I}{O_E}\right] \cdot 100$$

where K_U is the efficiency coefficient of forest road, O_E is the effective opening-up area (ha), and O_I is the ineffective
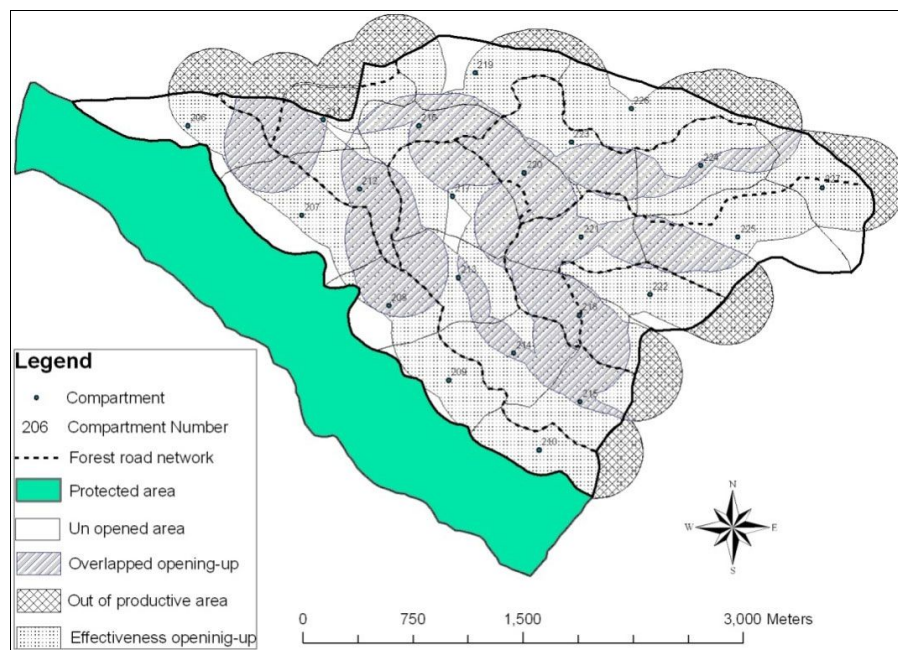

Fig. 2 - Effective opening-up and dead zone areas.

opening-up area, *i.e.*, the overlapped buffer opening-up and the part of buffers falling outside the district area (ha).

Results

Average existing real mean skidding distance

To calculate the existing real mean skidding distance, the existing geometrical mean skidding distance in each compartment was multiplied by the correction factor (K_G) of 1.58, as reported by Pentek et al. (2005). The average existing real mean skidding distance (Sd_{ER}) at district level was estimated taking into account the harvesting volume (E) and existing real mean skidding distance (Sd_{ER}) in each compartment (Tab. 1), obtaining a value of 310 m (eqn. 6):

$$\overline{Sd}_{ER} = \frac{\sum_{i=1}^{n} Sd_{ER(i)} \cdot E_i}{\sum_{i=1}^{n} E_i} = 310m$$

Optimum road network density

The forestry center of the Kheyroud Educational and Research Forest has defined and reported the costs of road construction and maintenance. To have a set of comparable costs - as different road sections have been

constructed in different times -, the cost of each section was actualized to a certain year, using the average interest rate of the Iran Central Bank. According to the above forestry center report, the annual road construction cost and road maintenance cost were estimated 52.5 US$ m^{-1} year^{-1} and 1.1 US$ m^{-1} year^{-1}, respectively. Value of the annual road amortization cost over a period of 50 years was 2.2 US$ m^{-1} year^{-1}. The average harvesting volume calculated using weighted averages was 6.2 m^3 h^{-1}. Skidding operations in the study area is carried out by a contractor company, whose costs are 25 US$ m^{-3}, with no variable or fixed skidding cost. Considering the skidding cost (25 US$ m^{-3}) and distance (310 m), the parameter F takes the value of 0.042 (eqn. 7):

$$F = \frac{25}{310} \cdot 0.517 = 0.042$$

Majnounian et al. (2009) reports values for the total correction factor (K_S) for Kheyroud Forest from 2 (gentle slope) to 2.63 (steep terrain). We used $K_S = 2.3$, because Namkhaneh district area extends over low and steep terrain (mean slope angle 35%) and due to the both sides skidding, a value of 0.575 was used in the eqn. 1. Finally, the optimum road density value obtained (D_O) was 21.5 m ha^{-1}.

Tab. 2 - O_R and K_U of existing forest road network. (O_T): total opening-up area; (O_D): double opening-up area; (O_O): outer opening-up area; (O_I): ineffective opening-up area; (O_E): effective opening-up area; (O_R): relative openness; (K_U): efficiency coefficient.

Harvesting area (ha)	O_T (ha)	O_D (ha)	O_O (ha)	O_I (ha)	O_E (ha)	O_R %	K_U %
788	1192	328	154	482	710	90	32

Average optimum geometrical mean skidding distance

Considering, D_O = 21.5 m ha^{-1} and K_S = 0.575, the average optimum real mean skidding distance was 267 m (eqn. 8):

$$Sd_{OR} = \frac{0.575}{21.5} \cdot 10000 = 267 \, \text{m}$$

As the buffers are formed on the road network layout using the geometrical skidding distance, the average optimum geometrical mean skidding distance (Sd_{OG}) was calculated using K_G = 1.58 (eqn. 9):

$$Sd_{OG} = \frac{267}{1.58} = 168 \, \text{m}$$

Relative openness

The relative openness was calculated dividing effective opening-up by the total district area (Tab. 2 - eqn. 10):

$$O_R\% = \frac{710 \, \text{ha}}{788 \, \text{ha}} \cdot 100 = 90\%$$

Efficiency coefficient of the forest road network

Effective opening-up was 710 ha and ineffective opening-up (the area of buffers either overlapping or falling outside the district area) was 482 ha. Therefore, the forest road network efficiency coefficient obtained was 32% (Tab. 2 - eqn. 11):

$$K_U\% = \left[1 - \frac{482 \, \text{ha}}{710 \, \text{ha}}\right] = 32$$

Discussion

The popular method by Matthews (1942), commonly used to assess a forest road network efficiency, is unsuitable for Caspian forests because its assumptions do not hold in the context analyzed. In this study, to calculate the real skidding distance and optimum road network density, two correction factors were considered. The current road density was 20 m ha^{-1} and the current average mean skidding distance using the center of gravity method was 310 m. The obtained value for optimal road density (21.5 m ha^{-1}) considering road construction and maintenance costs, skidding cost and the harvesting volume, was a slightly higher than the actual road density. According to the Iranian Plan and Budget Organization (IPBO), a value of 20 m ha^{-1} is considered as the optimum road density for the current logging and transportation system in the Caspian forests (IPBO 2000). Moreover, Lotfalian (2002), considering a ground skidding system (Timber Jack 450C) and different characters (*i.e.*, slope, skidding cost, correction factors, soil type, etc.) in the Sangdeh forest (northern Iran), reported an optimum forest road density (21 m ha^{-1}) comparable with the results of this study. Therefore, the value 21.5 m

ha^{-1} can be suggested as an optimal and economical density for road network in the Caspian forests, as well as in regions with terrain conditions, logging and wood extracting methods similar to our study area.

Optimal average mean skidding distance, relative openness and efficiency coefficient of the studied forest road network were 267 m, 90% (excellent openness) and 32%, respectively. Based on the results obtained, the actual road density in the area (20 m ha^{-1}) is roughly adequate. However, the low value of the efficiency coefficient (32%) suggests that the studied road network do not present a proper distribution. In other words, road networks with a low efficiency coefficient may lead to habitat and biodiversity losses in the future, due to forest fragmentation into smaller and more isolated patches as a consequence of sub-optimal harvesting practices (Chomitz & Gray 1996, Forman et al. 1997, Geneletti 2003, Hui et al. 2003). Based on the relative openness only, the forest road network seems to show a well opening-up and function. On the other hand, the road network efficiency coefficient obtained indicates a fairly high level of ineffective opening-up. Therefore, it can be concluded that road network efficiency is lower than the value that of relative openness indicated. Analogously, Pentek et al. (2005) reported the relative openness (81.4%) and the efficiency coefficient (42.37%) of a forest road network in Croatia.

In the Caspian forest, the relative openness is commonly used as a suitable indicator for the selection of the best road network variants (*e.g.*, Goudarzi 1999, Sepahvand 2004, Puya et al. 2009). Nonetheless, in this investigation, despite a very good relative openness (90%), the efficiency coefficient of the studied road networks were not satisfactory (32% only). It may thus be suggested that the road network efficiency coefficient, that considered the ratio of ineffective to effective opening-up, is a more reliable indicator of the forest road network quality and efficiency.

Conclusion

Forest road network plays an important role in sustainable forest management, which has to be planned as much optimally as possible. To achieve an optimal road network with low-costs and high-quality, the following points are recommended:

- taking into account all the economical parameters such as the skidding costs, road construction and maintenance costs for the road network optimization;
- taking into account the harvesting volume and the possible secondary forest products, because they can also increase road network density;
- considering the efficiency coefficient to analyze the quality of the forest road net-

work variants, as showed in this study, it is a more precise indicator for the qualitative evaluation and optimization of a forest road network;

- considering other functions of forest roads like ecotourism, forest fire extinction, etc, in forest road network assessment.

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