Impact of rainfall intensity and cutslope material on sediment concentration from forest roads in northern Iran

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Forest roads are important for adequate management of natural resources, but they are also a dominant contributor of sediment to forest streams and water pollution. This study measured road sediment concentration from forest roads to determine the impact of rainfall intensity and cutslope types on sediment concentration in the Patom district of northern Iran. Two 110 m road segments with variable soil and rock fragment cover exposed at the cutslopes were studied. Seven rainfall and corresponding runoff events were measured in 1-liter bottle samplers every 10 minutes at the outlet of cross sectional culverts, and from two 3 m² plots on the roadbeds adjacent to each cutslope. A statistically significant difference at the 95% confidence level between two cutslope types and rainfall intensity on sediment concentration was determined from the field data based on nonparametric tests, though no statistically significant difference in the concentration of sediment between the two roadbeds plots were found. The average of sediment concentration of soil trench and the rock fragment cover cutslopes were 60.3 and 46.8 g/l, respectively. The results reported here should help forest road managements to improve the understanding of cutslopes erosion and sediment production from forest roads and to employ suitable methods to reduce sediment production.

Keywords: Forest Road, Cutslope, Rainfall Intensity, Rock Fragment, Sediment Concentration

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 (Hayati et al. 2012). In order to facilitate forestry operations in managed areas, a well developed network of roads is fundamental (Abdi et al. 2012), providing access for management, wood utilization, ecotourism activities and fire control. In this context, suitable forest roads are crucial for sustainable management of forest resources. Nonetheless, forest roads are also recognized as a major source of erosion and can account for as much as 90% of all sediment production in forested watersheds (Swift 1984). Erosion and sediment delivery to forest streams is a source of water pollution and global management problems. Previous studies have indicated that erosion rates are very low in natural and undisturbed forests (Dunne 2001, Ramos-Scharrón & MacDonald 2007, Elliot et al. 2009). Sediment production rates from unpaved road surfaces have been estimated several orders of magnitude higher than undisturbed hillslopes (MacDonald et al. 1997, 2001, 2006, Croke et al. 1999). Forests roads cause many local changes in the forested environments and induce changes to soil properties and hydrologic behavior of hillslopes, increase soil erosion and the incidence of mass movements (Gresswell et al. 1979, Sidle et al. 1985, Larsen & Parks 1997, Gucinski et al. 2001). The main factors that cause increased sediment delivery to forest streams are removing plant cover along the forest road pathway, compaction of the soil in the roadbed, interception of surface and sub-surface flows, constructions of cutslopes, and alteration of hillslope water pathways (Tague & Band 2001). Sediment delivered to forest streams cause water resource pollution, filling dams and may have impacts on aquatic habitat (Damian 2003, Refahi 2006, Khalilpoor et al. 2008, 2010).

Three methods are typically used to measure sediment produced from forest roads: (1) measurement in natural conditions with natural precipitation events (*e.g.*, direct measurements from outlet of live streams culverts or using sediment traps - Lewis 1996, Luce & Black 1999, Sheridan et al. 2006, Meadows 2007, Surfleet 2008); (2) use of a rainfall simulator (Jordán-López et al. 2009, Foltz et al. 2009); and (3) use of empirical and physical sediment prediction models (Akay et al. 2008, Elliot et al. 2009, Khalilpoor et al. 2010). Although field quantification methods are costly and time consuming (Fu et al. 2010), they should be preferred because sediment delivery occurs most efficiently at road-stream crossing where virtually most of the generated sediment is delivered to the streams (Lane & Sheridan 2002, Croke et al. 2005).

A potentially important contribution to forest road sediment production may come from cutslopes (Luce & Black 1999, Jordán-López et al. 2009). Ramos-Scharrón & MacDonald (2007) showed that cutslope areas are responsible for about 9% of the total road segment sediment production. Luce & Black (1999) examined the relationship between sediment production and road attributes such as distance between culverts, road gradient, road texture, and vegetation cover on cutslope. Their study indicated that sediment production was not correlated to the cutslope height, but sediment yield from cutslopes with cleared vegetation cover was about 7 times more than from road segments where vegetation was retained. Akay et al. (2008) estimated sediment from forest roads delivered to streams using the SEDMODL model and GIS techniques. They showed that reducing rock cover of cutslopes caused a significant increase in sediment yield. In addition, they showed that in seasons with high intensity rainfalls, a considerable amount of sediment production in road sections with low quality surfacing might occur. Ramos-Scharrón & MacDonald (2007)

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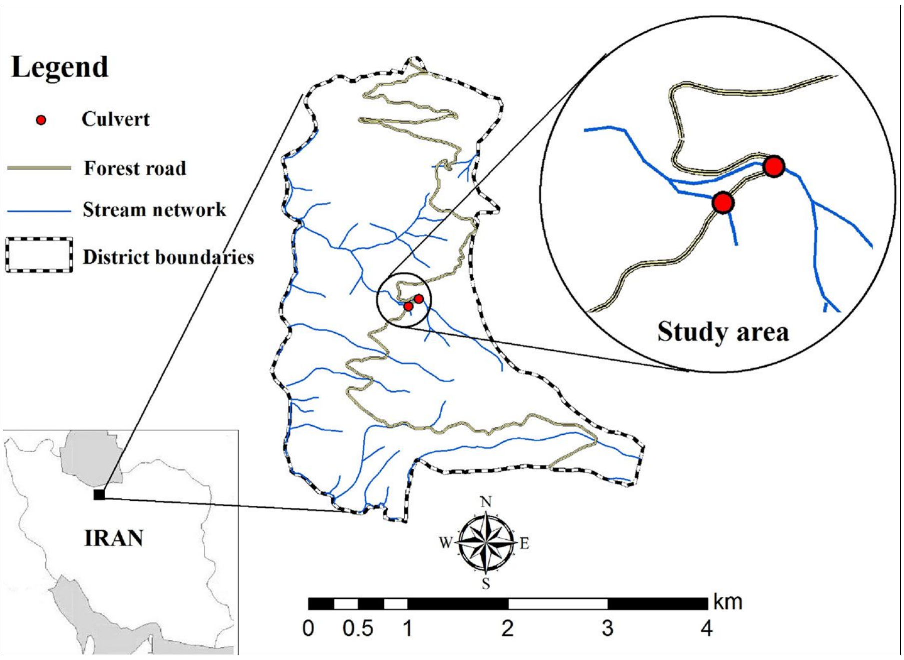

Fig. 1 - Road network of Patom district (northern Iran) and location of studied culverts.

quantified sediment production and delivery rates in a dry tropical environment. They reported that cutslope sediment rates ranged from 20 to 170 Mg ha^{-1} yr^{-1}, and unpaved roads had sediment production rates between 57 Mg ha^{-1} yr^{-1} for road with 2% slope up to 580 Mg ha^{-1} yr^{-1} for a road with 11% slope. Moreover, their study showed that unpaved roads were a dominant source of sediment and responsible for a 3-9 times increase in watershed-scale sediment yield relative to undisturbed conditions. López et al. (2008) in the Mediterranean area measured the impact of different parts of unpaved forest roads on runoff and sediment yield. They used a simple portable rainfall simulator on the cutslope, fillslope, and on the roadbed. They showed that cutslopes are the main source of sediment on forest roads with 486.7 g m^{-2} per storm. Total soil erosion on cutslopes was 3 and 18 times higher than those from the roadbeds and fillslopes, respectively.

Given the importance of erosion and sediment production from forest roads, knowledge of the road segments potential for erosion and impact of rainfall intensity on sediment production can help forest managers to identify sensitive segments for erosion control operations. Therefore, the objectives of this study were to: (1) assess the effect of different rainfall intensities on forest road sediment concentration; and (2) assess the role of two different cutslope types in sediment concentration in the Patom district in Iran.

Material and methods

Study site

The study area was located in the Patom district in the Kheyrud Forest Research Station of Tehran University, which is located at approximately 36° 38' N and 50° 34' E (Fig. 1). The Patom district has a 900 ha drainage area and ranges from 0 and 934 m a.s.l. in elevation. Average annual rainfall is 1300-1500 mm. The mean air temperature is 16.1 °C. The average of stand volume is about 55.76 m^3 ha^{-1}, dominant stand height 25-30 meters, 70% canopy cover and 263 stems ha^{-1}. Dominant tree species are *Carpinus betulus* (Hornbeam), *Fagus orientalis* (Oriental Beech) and *Parrotia persica* (Persian Ironwood). The lithological substrate is mainly calcareous parent material and the associated soil types are Inceptisols and Alfisols (Sarmadian & Jafari 2001). The length of the road network in the district is 16.3 km, with an average density of 18.1 m ha^{-1}. Unpaved forest roads ascending from 620 m to 650 m a.s.l. were selected for this experiment. This road is used by wood utilization vehicles such as tracks and skidders and other passenger cars such as jeeps and touring cars.

Methods

All culverts from the Patom district's road were geo-referenced using a GPS receiver (GARMIN, COLORADO 300) and were exported to ArcGIS Desktop 9.3 as a map layer. Two live stream culverts along the road network were selected for sediment measurements after field observation, each representing two different types of cutslopes. Vegetation cover and rock fragment cover were determined using a 50 cm × 50 cm grid with cells of 0.25 cm^2 (Jordán-López et al. 2009). The slope angle of the soil surface on each cutslope was determined using a clinometer. Two selected cutslopes were similar in averages, with 30% gradient, 3 m slope length, and about 10% vegetation cover, but they were different in material. One cutslope had exposed more than 70% of soil (henceforth named "Soil Cutslope"), and the other had exposed more than 70% rock fragment cover (named "Rock Cutslope"). The width of the road was about 5.5 m with a moderate gradient ranging between 6-11% (Lewis 1996). The other road characteristics were the same for two road sections (Tab. 1).

On both road segments, two 3-square-meters (3×1 m) bordered plots (3 m selected as plots length because it was equal to cutslopes slope length) were located randomly and installed using sheet metal borders with a runoff apron on the roadbed surface at the bottom of road length slope. The plots were named "Rplot" and "Splot" as they were located on the roadbeds associated to "Rock Cutslope" and "Soil Cutslope" road segments, respectively. Seven rainfall events were measured with a cylindrical, manual rain gauge, and samples of the sediment suspended were collected in 1-liter sampler bottles at every 10 min intervals from roadbed plots and at the outlet of culverts that accommodates runoff from roadbeds and cutslopes.

Sediment suspended concentration was carried out by decanting and filtering through a Wathman No. 42 paper under suction on a Buchner funnel in the lab (Gordon

Tab. 1 - Relevant characteristics of the cutslopes considered in this investigation.

Characteristic	Soil cutslope	Rock fragment cutslope
Lithology	Calcareous	Calcareous
Soil	Inceptisol & Alfisol	Inceptisol & Alfisol
Gradient (classify)	Medium	Medium
Travel way material	Graveled	Graveled
Vegetation cover	Non (Removed)	Non (Removed)
Width (m)	5.5	5.5
Age (years)	24	24
Length (m)	110	110
Cutslopes	>70% soil	>70 rock fragment

et al. 2004). Papers containing sediment were then weighted and placed in a drying oven for 24 hours at about 105 °C (Malomo et al. 1983).

The sediment contribution from cutslopes at the road segment scale was derived by subtracting roadbed sediment from the sediment that flows to the culvert outlet, which contains runoff from both the roadbed and the cutslope.

Average rainfall intensity was obtained by dividing rainfall height (mm) to rainfall duration (hour). According to Mahdavi (2005) average rainfall intensity was classified as follows: (1) light rain (intensity < 2.5 mm h^{-1}); (2) moderate rain (intensity between 2.5 and 7.5 mm h^{-1}); and (3) heavy rain (intensity > 7.5 mm h^{-1}).

Data analysis

Kolmogorov-Smirnov normality test (α = 0.05) was initially applied to verify normal distributions of the variables considered (Rodríguez-Pérez et al. 2007). Kruskal-Wallis test was used to verify the null hypothesis of no impact of rainfall intensity on the sediment production from forest roads, while Mann-Whitney U test was applied to verify the null hypothesis of no differences in sediment productions from the two cutslope types (Rodríguez-Pérez et al. 2007, Jordán-López et al. 2009).

The relationship between average rainfall intensity and sediment concentration to the road culverts was analyzed using simple regression analysis of log-tranformed data.

Results

Seven rainfall events were measured and classified as light rain, moderate rain and heavy rain. Rainfall intensity ranged between 2.2 up to 10.8 mm h^{-1} in the studied area. The number of rainfall events and the number of samples considered for each plot is reported in Tab. 2.

All the variables analyzed did not show significant departures from normality after Kolmogorov-Smirnov test ($P \geq 0.05$ - Tab. 3). Pooling data from the two plots analyzed, significant differences ($P \leq 0.001$) among rainfall intensity classes were found after Kruskal-Wallis ANOVA: as rainfall intensity increases, sediment delivery increases accordingly (Tab. 4).

Significant differences in sediment delivery were also observed between the two cutslop types considered (Kruskal-Wallis ANOVA - $P \leq 0.001$). Hence, sediment concentration increased with rainfall intensity for both segment roads, but sediment concentration for the soil dominated cutslope was significantly higher than the rock dominated cutslope for any rainfall intensity class (Tab. 5).

Mann-Whitney non-parametric test applied to data pooled over rainfall classes revealed significant differences between the two cutslope types (P = 0.024), confirming that on average sediment produced from the soil cutslope was higher than the rock fragment cutslope. On the other hand, we did not find any significant difference between Rplot and Spolt for the two roadbeds associated to the cutslopes (Tab. 6).

Results from the regression analysis showed that the relationship between the average rainfall intensity and the sediment concentration to the culverts from the two roads fits fairly well to a logarithmic function (Fig. 2). It is worth to notice that differences in sediment concentration between the two cutslope types becomes obvious for high-intensity events, while both types have very similar concentrations for low-intensity values of rainfall intensity.

Tab. 2 - Number of rainfall events and sediment samples in each rainfall intensity classification.

Parameters	Rainfall event	Samples
Light rain	1	39
Moderate rain	4	36
Heavy rain	2	32
Total	7	107

Tab. 3 - Results of Kolomogrov-Smirnov Normality Test. (N): number of samples collected during rainfall events.

Normality test	Soil Cutslope ± SD	Rock Cutslope ± SD
Mean	60.32 ± 16.41	46.79 ± 26.42
N	57	50
Prob.	0.469	0.58

Tab. 4 - Relationship between rainfall intensity classes and total sediment concentration (g/L). Kruskal-Wallis ANOVA, P ≤0.001**.

Rainfall Classes	Mean Sediment Concentration (g/l) ± SD
1	14.9 ± 6.81
2	52.2 ± 21.32
3	74.1 ± 30.56

Tab. 5 - Relationship between rainfall intensity classes and sediment delivered from road with rock fragment cutslope. Kruskal-Wallis ANOVA, P≤0.001*.

Rock Cutslope		Soil Cutslope	
Rainfall classes	Sediment mean (g/l) ± SD	Rainfall classes	Sediment mean (g/l) ± SD
1	6.0 ± 3.1	1	9.5 ± 4.7
2	16.6 ± 7.5	2	26.1 ± 11.3
3	32.4 ± 15.8	3	42.7 ± 21.4

Discussion

In undisturbed forest systems, the kinetic

Tab. 6 - Mann-Whitney test to compare sediment concentration from two cutslope types and roadbeds plots.

Cases	Mean of Sediment (g/l) ± SD	Sediment Percentage (%)	P
Soil Cutslope	60.3 ± 26.4	91	0.024*
Splot	6.1 ± 2.9	9	-
Rock Cutslope	46.8 ± 16.4	80	0.215
Rplot	11.6 ± 7.4	20	-

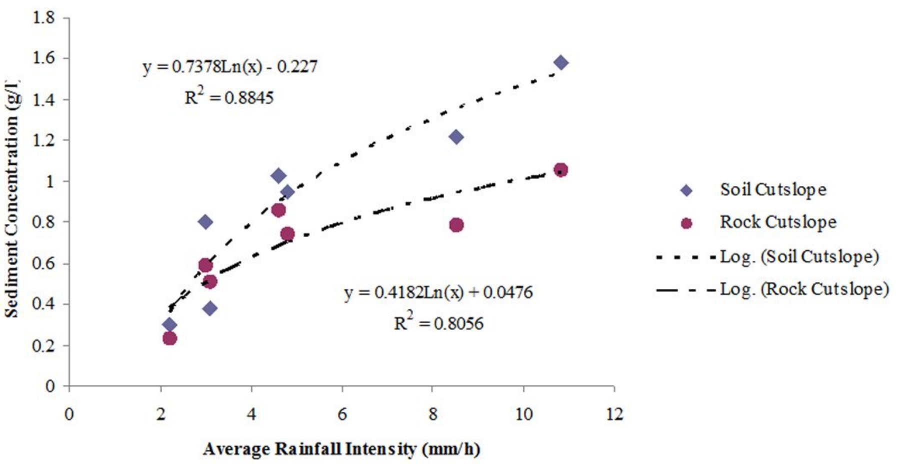

Fig. 2 - Logarithmic relationship between average of rainfall intensity and sediment concentration.

energy of raindrops or water flow on the surface are reduced by tree canopy and soil litter, thus lessening soil erosion. Wischmeier & Smith (1958) observed that kinetic energy of rainfall increases with rainfall intensity with a logarithmic rule. Young & Wiersma (1973) showed that the impact energy of raindrops is the major force initiating soil detachment in a rainfall-simulation on three different soils. The mechanism by which a soil particle is detached from bulk soil mass is tensile failure (Nearing et al. 1991). The soils particles must be detached from the bed against the resisting force of inter aggregate cohesion and their weight. Therefore when rainfall intensity increases, kinetic energy increases and soil particles with bigger size detach. Some of the soil big particles settled or trapped by vegetation and rubbles in the runoff path, also vegetation dissipates the runoff energy, this cause increases sediment with rainfall intensity had logarithmic relationship not linear relationship (Fig. 2, Tab. 4, Tab. 5). MacDonald & Coe (2008) indicated that one factor affecting surface erosion from forest road surface is rainfall intensity (Fig. 2). Akay et al. (2008) indicated that the effect of total precipitation was low on sediment production, but considerable amounts of sediment are produced during intense rainfall events. This is in agreement with our results, as different amounts of sediment were produced from cutslopes under different rainfall intensities (Tab. 4, Tab. 5).

The two roadbed segments associated to the two cutslope types were similar as for the material (Tab. 1) and construction method; we expected that sediment concentration from these segments would not display significant differences, and this hypothesis was supported by our findings (Tab. 6). So cutslope sediment concentration was derived by subtracting roadbed plots sediment to sediment samples collected from the outlet of culverts that accommodates runoff from roadbeds and cutslopes in each rainfall event. Our hypothesis agreed with our finding that roadbeds with similar materials and construction methods do not have a statistically different sediment concentration (Tab. 6) and therefore any difference in sediment concentration at the road outlet is due to the differences in the cutslope properties.

According to Poesen & Lavee (1994) the influence of surface rock fragments on sediment yield from bare interrill areas largely depends on the effects of rock fragments on sub-surface flow and on sediment concentration. On the cutslope the rock fragments at the surface increased the roughness and the interception of raindrops, reducing soil detachment and sediment production. Jordán & Martínez-Zavala (2007) observed that, in non-vegetated cutslopes, rock fragment cover may protect the soil surface from erosion. López et al. (2008) stated that the cutslope cover and rock fragment on soil texture are important factors for reducing runoff and sediment production. These results support our finding that cutslope material and type is effective on the sediment production.

Due to compaction of the soil surface, roadbeds had lower sediment concentration than cutslopes (Tab. 6). This finding is supported by Jordán & Martínez-Zavala (2007) and López et al. (2008) who showed that sediment produced from roadbed was lower than cutslope.

Soil losses from forest roads require reconstruction and maintenance costs, and these encompass the majority of costs in forest management plans (Abdi et al. 2010). Sediment suspended cause forest streams and aquatic habitat pollution. Boyd (1990) observed that sediment suspended concentration higher than 20 g/l in streams cause confusion and disorder in the behavior of aquatic species. Although this study did not measure sediment suspended concentration in forest streams and aquatics habitats, it provides some information for forest managers to consider the roadbed and cutslope surface, and method to reduce sediment production and reduce stream pollution.

Conclusions

The cutslopes are the main source of sediment production (80-91%) on forest roads in northern Iran. For the two roads and road cutslopes, measured rainfall intensity was an important factor on detachment and delivery of sediment to streams.

Increasing rainfall intensity increased sediment concentration from two forest road segments. The road with a cutslope dominated by loose soil produced runoff with a higher sediment concentration than the cutslope dominated by a rock fragment cover.

Rock fragment cover is an important factor that conditions sediment concentrations on the road cutslopes. Also sediment produced from roadbeds was lower than cutslopes and there was not significant difference between two roadbeds with similar materials, construction method and age.

Forest roads managements should pay more attention to more sensitive sections of forest roads and road maintenance activities (such as increasing plant cover or rock fragment percentage) in order to reduce sediment production and prevent water pollution.

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