THE EFFECTS OF RILL EROSION ON UNPAVED FOREST ROAD

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Abstract. This research aims to investigate the degree of rill erosion and its relationship with the factors effective on rill volume on unpaved forest roads in Bartın Province in Turkey. For this purpose, measurements were made at 380 sample locations on different regions of the forest roads in Arıt and Hasankadı sub-districts. The measurements were performed on 4 years old unpaved forest roads. Among the road surface (RS), road cut (RC), sidecast fill (SCF) and skid trail (ST) road sections, RS and ST ranked as the first two sections with the highest segment length. Segment length is characterized as the most effective field factor on erosion, which further increased the rill volume by the combined effect of increasing slope, in this research. According to the stepwise (forward-backward) regression analysis results, inclusion of both segment length and slope parameters in the RS, SCF and RC equations supports this finding. The correlation of all road sections (RS, SCF, RC, ST) with the segment length are 0.84, 0.63, 0.75 and 0.83, respectively, and the correlation with the slope are 0.55, 0.73, 0.57 and 0.64, respectively. As a result of the slope-based categorization of the relationship between segment lengths and rill volume for the road sections, R^2 values were found to increase up to 0.88 for RS, 0.78 for SCF, 0,94 for RC and 0.88 for ST. The rill volume at short and steep roads can be lower than the rill volume at long and low-slope roads. Therefore, we calculated the rill volumes per unit road segment area. As a result of application of equations based on shear stress and stream power sediment transport capacity theory, RMSE values with very low mean error were obtained. In further related studies, drainage areas in addition to segment lengths and slope should also be taken into account to determine the positive and negative effects in evaluation of rill erosion amounts. Also, similar studies should be performed on other basins having a larger number of unpaved forest roads as a means to extend the applicability of the obtained findings.
Keywords: *soil loss, road erosion, sediment sources, hydrological constituents, unpaved road*

Introduction

Unpaved forest roads cover a relatively tiny area of a basin, though they have a major effect on numerous hydrological and geomorphic processes in a given basin and they act as a primary sediment source, which make them an interesting subject for various research (Megahan, 1987; Luce and Wemple, 2001; Ramos-Scharron and MacDonald, 2005; Cao et al., 2011, 2014, 2015). The combined effect of soil compaction resulting in reduced infiltration capacity of road surface and the vehicle-induced increase in the sediment yield leads to an increase in surface runoff (Sidle et al., 1985; Ziegler et al., 2000; Croke and Mockler, 2001; Gucinsky et al., 2001; Dougherty et al., 2004; Xu et al., 2007; Eisenbies et al., 2007; Cao et al., 2011; McGroody et al., 2013). This formation occurs even to a greater extent than mass movements (Ketcheson et al., 1999). It has been reported in studies performed in various locations (Australia, China, England, Ghana, Kenya, Kuwait, Malaysia, New Zealand, Norway, Poland, The

United States, Tunusia etc.) that, forestlands feature lower erosion whereas unpaved forest roads exhibit significantly higher erosion (Dunne, 1979; Reid and Dunne, 1984; Kumapley, 1987; Fahey and Coker, 1989; Burroughs et al.,1991; Froehlich, 1991; Douglas, 1993; Grayson et al., 1993; Froehlich and Walling, 1997; Fransen et al., 2001; Xu et al., 2009; Posthumus et al., 2011; Tommervik et al., 2012; Foster et al., 2012; Al-Awadhi, 2013; Desprats et al., 2013; Leh et al., 2013). In this regard, evaluation of the sediment yield of unpaved forest roads gains an increasing importance.

As a result of the higher erosion rates on unpaved forest roads compared to open-channel flow areas or areas with heavy vegetation (such as agriculture and pasture areas), data specific to such areas have been used in estimation of road-induced sediment in the last fifty years (Ramos-Scharron and MacDonald, 2007; Croke et al., 1999). Particularly, conducting an effective land planning requires a good understanding of road-induced erosion and sediment production process. River monitoring, sediment determination methods and road erosion models are widely used to estimate the road-induced erosion. Silt fences, installed on road sites, provide useful information at coarse grained (such as sand and gravel) roads, but they do not provide precise information in determination of fine sediment yields (Ramos-Scharron and MacDonald, 2007). Besides their convenience, monitoring methods are more costly.

SEDMODL2 (Road Sediment Delivery Model), WARSEM (Washington Road Surface Erosion Model), CULSED, USLE (Universal Soil Loss Equation) and its modifications, and ROADMOD are the test based models; whereas WEPP (The Water Erosion Prediction Project) and KINEROS2 (Kinematic Runoff and Erosion Model) are physical models used in estimation of sediment yield (Dube et al., 2004; Cochrane et al., 2007; Elliot et al., 2009; Fu et al., 2010; Cao et al., 2011; Varol, 2015, 2016). Considering the statistical relationship between the observation-driven results derived from experimental models and dependent variables, the use of these models in diverse studies becomes a challenge due to their field-specific nature (Merritt et al., 2003). Physical models are mainly based on hydrological reactions and these models simulate infiltration and run-off routines. Case-based models, on the other hand, estimate the sediment yield produced as a result of a single rainfall or run-off event, thus simulating the erosion. Moreover, experimental models are continuous, whereas physical models are case-based models.

As reported in the studies performed on unpaved forest roads in Turkey; sediment yields vary between 0 - 2.715 tons on gravel-surfaced road sections, and between 1.476 - 28.667 tons on asphalt roads. Spatial sediment yield varies between 0.0004 t/m^2 and 0.0199 t/m^2 on gravel surfaced grounds, and between 0.0051 t/m2 and 0.0636 t/m^2 on asphalt roads (Akay et al., 2008). In addition to the afore-stated studies quantitative works on soil erosion characteristics of unpaved roads are also required (Xu et al., 2009; Varol, 2016). Investigation of erosion characteristics is particularly required for steep unpaved forest roads that receive large amounts of rain such as those in Karadeniz Region. GPS aided road surveys and GIS methodology have been commonly used in investigation of road-induced erosion characteristics as these are closely associated with road types and spatial variables. In this regard, the present research was conducted at Arıt and Hasankadı Sub-district Directorates of Bartın Forestry Directorate with a view to: (1) define the amount and spatial distribution of road erosion, (2) clarify the relationship between the road segments' erosion characteristics and the effective factors, and (3) propose equations that can be used in estimation of erosion.

Material and method

Study area

The erosion estimation studies for unpaved forest roads were performed in Arıt (32° 24' 20"- 32° 44' 50" east longitudes and 41° 33' 90"- 41° 45' 70" north latitudes) and Hasankadı (41° 17' 48" - 41° 22' 35" north latitudes and 32° 16' 48" - 32° 29' 06" east longitudes) sub-district directorates of Bartın Forest Directorate in Turkey (*Fig. 1*). The region is dry and hot in summers (Csa) (Varol and Ertugrul, 2015) with a mean yearly temperature of 12.8 °C, and annual precipitation is 1044.5 mm (1965-2017 The total rainfall in 2017 in which the study was carried out was 1209.3 mm above the average of 1965-2017 period. In 2017, the highest monthly rainfall amounted to 242.7 mm in August. The sample unpaved forest road locations surrounded with forestlands in both sub-districts are located in basins with about 17.4 (14.6 + 2.8) km² acreage and their altitudes above sea level vary between 750 and 1200 m. Both road sections are in Kilimli formation and they are composed of Cretaceous aged bedrock sandstone-carbonate sand-stone. In the study area, agricultural and settlement areas in Arıt sub-district cover the largest area (7.74 km²) which are followed by fertile (6.14 km²) and rough (0.7 km²) forestlands and forest soil. Hasankadı sub-district is completely composed of fertile forestlands (2.87 km²).
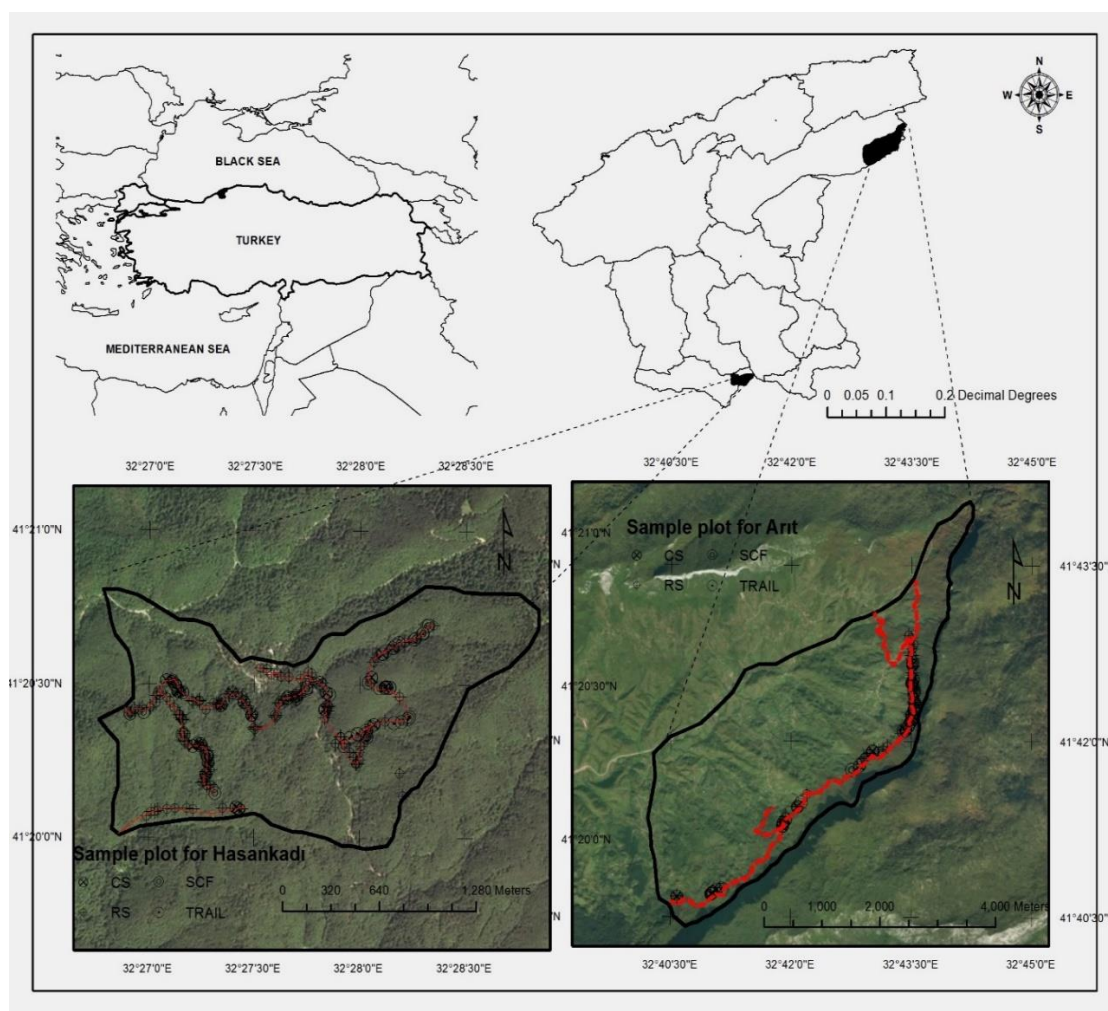

Figure 1. *The location of study area*

Road network

A forest road consists of a series of hydrological constituents such as road surface (RS), road cut (RC) and sidecast fill (SCF) (*Fig. 2*). Road surface represents the unpaved surface of the road on which vehicles move, road cut represents the straightly or curvedly cut profile of the slope of the road, and sidecast fill defines the aggregates right under the road that forms during road construction. No vegetation is observed on the road cut sections that have an average height of 2-5 meters and the sidecast fill sections that have straight profiles. Segment lengths observed in the study area vary between 5.0-285.7 m for road cut segment, 3.5-477.3 m for road surface, 2.9-99.6 m for sidecast fill, and 2.2-102.4 m for skid trails.
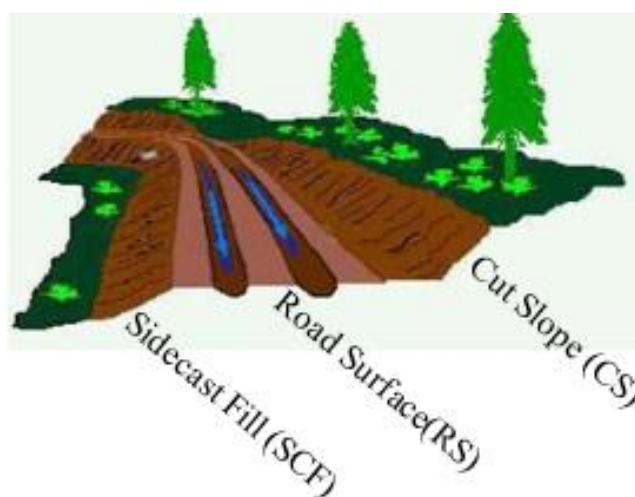

Figure 2. Components of a road (Elliot et al., 2009)

The total forest road length of Arıt sub-district is 148610 m, and that of Hasankadı sub-district is 115700 m. All forest roads in Arıt sub-district are B-type secondary forest roads (The platform width is 3-5 m, ditch width is 0.50-1 m, total width of 3.5-6 m, the minimum curve radius is 12 m, maximum slope 12%, which are generally unpaved roads. The annual amount of product to be transported on these roads is less than 25000 m³) and only 3% are paved forest roads. Those in Hasankadı sub-district are also B-type secondary forest roads and 30% are paved forest roads. Accordingly, the roads in both sub-districts are largely void of road pavement to bear the vehicle loads. These roads have been used for transportation purposes by local residents in addition to forestry and agricultural activities. These roads do not have any surface cover. Compacting is materialized by the vehicles used in agricultural and forestry activities. The newly constructed roads in the road network plan were manually digitized and involved in the network plan. The road surface, road cut and sidecast fill sections of the study area were constructed four years before 2017, skid trail sections were constructed ten years ago. In parallel to the increasing run-off followed by rainfall, surfaces of unpaved forest roads lead to increasing sediment transport. Sediment transport occurs at higher rates at rills that form on the road segments (RS, RC, SCF) (*Fig. 3*). Therefore, rill formations on each road segments have been subject to examination in this research. In general, a road segment is characterized with the road length between two nodes (Tanimoto, 1999; MacDonald et al., 2001).

Figure 3. *Unpaved road segment samples. **a** Sediment transport along the rills that form on the road segment. **b** Highly eroded road surface. **c** Erosion on the node where two road segments intersect*

A road segment can be terminated by intersection of the node with another road or an artificial boundary, or it can start and end by a change in road characteristics (such as slope, exposure, etc.). A road segment can be defined as a section of the rode with an independent drainage area (Cao et al., 2014). During the road measurements, the start and end points of road segments in addition to the segment lengths and variations in slope were determined via GPS. The characteristics of the road network and road segments on which the measurements were performed are shown in *Table 1*.

Table 1. *Characteristics of the road network and road segments in the study area*

Road type and segments	Road network's characteristics			Road segments' characteristics			
	Total length (km)	Mean width (m)	Road density (km/km²)	Count	Mean length (m)	Ratio of rilled segment (%)	Mean slope (%)
RS	14.7	6.11	0.84	206	60.89	40.85	9.42
SCF	14.7	5.94	0.84	48	24.66	50.61	37.62
CS	14.7	6.13	0.84	79	45.80	9.66	35.41
ST	1.9	6.00	0.11	47	28.97	68.86	29.65

RS: Road surface, SCF: Sidecast fill, RC: Road cut, ST: Skid trail

Data

The length, width and depth of rills on each specified road segment were measured by a measuring tape. The slope of rills and the road were measured by a clinometer. Intersecting rills were measured up to the point of junction with the main rill. As a means for an accurate estimation of the erosion on road segments, width and depth measurements were performed at three meter intervals. Measurements were conducted on a total of 427 rills at road surface, road cut, sidecast fill and skid trail sections.

The statistical evaluation of the relationship between slope and length of road segments, which are the effective factors on the amount of road-induced erosion, and erosion was carried out using ANOVA (one-way analysis of variance), Pearson correlation analysis, and RMSE (the root mean square error). ANOVA was used to make a comparison of rill volumes and road segments, Pearson was used for correlation analysis and evaluation of the relationship between the effective factors and road-induced erosion, and RMSE was used to evaluate the efficiency of the estimation models for soil erosion. RMSE is defined with the following *Equation 1* (Bhuyan et al., 2002).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}}$$
(Eq.1)

In *Equation 1,* O_i and P_i denotes the observed and estimated values, and n denotes the sum of each value pair. Smaller RMSE values indicate higher consistency between the estimated and the observed values.

Results and discussion

Road segments and rill characteristics

Significantly high ratio of rill were encountered on the skid trail and the road segments other than RC (*Table 1*). Ratio of rill depending on the road length were found as 40.85%, 50.61% and 68.86% respectively for RS, SCF and ST. The results show that, logging roads are subject to higher erosion than RS, and SCF despite being less frequently used and being subject to higher compaction. In general, the slope values of eroded road sections were found to be higher than the average values.

Although the determined erosion rates were higher for RS, erosion values per unit area (km) were found to be close to each other for RS and ST. The underlying reason

for RS's making the biggest contribution to road-induced sediment formation is its having the highest segment length, which results in the highest surface area. Formation of 227 rills on RSs (*Table 2*) supports this finding. Vehicle-induced disintegration of the road surface material also contributes to this situation. Despite the similar average widths of RS and ST at the sampling locations, the difference in the lengths of the two road segments affect rill formation and the resulting rill volume in favor of RS. A difference was also detected between RS and the other road segments after the ANOVA test ($p < 5.31 \cdot 10^{-7}$). In terms of the average rill lengths, RS and ST took the first two places, which further indicated that these road segments produced the highest amount of sediment (*Table 2*). This is mainly attributable to the higher distances at which run-off accumulation and repetition occurs for the mentioned road segments. Among the rill characteristics such as slope, length and volume, the latter two have been found to be more effective on sediment yield. The rill slope for RS is statistically significantly lower than the other road segments ($p < 2 \cdot 10^{-16}$). High sediment yield despite low slope value can be ascribed to the lower erosion strength of the surface material for RS; and higher erosion strength for SCF, RC and ST which are impaired to a lesser degree.

Table 2. Rill characteristics for different road segments

Road section	Rill count	Total rill volume (m³)	Soil loss per km (m³ km⁻¹)	Maximum rill volume (m³)	Average rill characteristics		
					Length (m)	Volume (m³)	Rill slope (%)
RS	227	97.56	6.64	5.60	19.22a	0.47a	5.84a
SCF	65	10.52	0.71	3.32	12.48a	0.22b	44.81b
RC	85	3.20	0.22	0.17	4.42b	0.04b	35.68b
ST	50	11.53	6.11	1.68	19.95c	0.24b	29.65c

RS: Road surface, SCF: Sidecast fill, RC: Road cut, ST: Skid trail

The factors that affect rill erosion

Unpaved forest roads exhibit the highest sediment yield values in all forestlands (Akay et al., 2008; Binkley and Brown, 1993; Mcclelland et al., 1999; Reid and Dunne, 1984). The sediment yield produced on the surface of the road is dependent on the traffic intensity, the surface type of the road, material characteristics, dimensions and the slope (Lang et al., 2018; Rhee et al., 2018; Erdem et al., 2018). Accordingly, the factors such as road, segment and rill lengths, rill volume, segment area and the slope of road segments were examined for determination of sediment yield from road segments and investigation of the relationships between the obtained data. These data are also used in several erosion models such as SEDMODL, FROSAM (The Forest Road Sediment Assessment Methodology), WARSEM, ROADMOD (Seutloali et al., 2015; Morgan and Nearing, 2016; Safari et al., 2016; Rose, 2017).

When the determined rill volumes were subjected to Pearson correlation test with the slope, segment length and segment area values, varying levels of significant relationships were found between the total rill volume and the stated variables for all road segments. The highest correlation among these variables was found between rill volume and segment length for all road segments (RS: $p < 2.2 \cdot 10^{-16}$ and $r = 0.84$, SCF: $p = 1.767 \cdot 10^{-6}$ and $r = 0.68$, RC: $p = 2.22 \cdot 10^{-15}$ and $r = 0.75$, ST: $p = 1.299 \cdot 10^{-11}$ and $r = 0.80$) (*Table 3*).

Table 3. *Relationship between rill volume and segment length, segment area variables*

Road section	Segment length	Segment area
RS	$p < 2.2 \ 10^{-16}$; r=0.84; t=22.593; df=204	$p < 2.2 \ 10^{-16}$; r=0.66; t=12.666; df=204
SCF	$p = 1.77 \ 10^{-6}$; r=0.63; t=5.473; df=46	$p = 3.03 \ 10^{-7}$; r=0.66; t=5.986; df=46
RC	$p = 2.22 \ 10^{-5}$; r=0.75; t=9.892; df=77	$p = 1.78 \ 10^{-15}$; r=0.75; t=9.954; df=77
ST	$p = 1.30 \ 10^{-11}$; r=0.80; t=8.992; df=45	$p = 7.24 \ 10^{-13}$; r=0.83; t=9.895; df=45

RS: Road surface, SCF: Sidecast fill, RC: Road cut, ST: Skid trail

The equations obtained after a collective evaluation of the variables such as slope, segment length and segment area with stepwise regression analysis (forward-backward) and resulting p and R^2 values are as follows (*Eqs. 2–5*):

For RS:

$$E = 1.11 \ L + 2.09 \ S - 24.03 \quad (p < 0.001; R^2 = 0.753) \quad \text{(Eq.2)}$$

For SCF:

$$E = 0.13 \ S + 0.25 \ L - 8.45 \quad (p < 0.001; R^2 = 0.433) \quad \text{(Eq.3)}$$

For RC:

$$E = 0.02 \ S + 0.02 \ L + 0.23 \quad (p < 0.001; R^2 = 0.632) \quad \text{(Eq.4)}$$

For ST:

$$E = 0.29 \ L + 0.34 \quad (p < 0.001; R^2 = 0.642) \quad \text{(Eq.5)}$$

P values are lower than 0.001 in all equations. In the equations, E is rill volume, S is slope, and L is segment length. As inferred from the equations, the combined effect of the increase in segment length and the increase in slope results in increased erosion. Similar results were also reported by Qin et al. (2018), Zhang et al. (2017), and Navarro-Hevia (2016).

As the road widths within the study area are either identical or very close to each other, the effective factor for rill volume in the segment area is the segment length. Therefore, the Pearson coefficients obtained for each road segment were similar for segment length and segment area. Moreover, as shown in *Table 3*, segment length and segment area yield similar results for SCF, RC and ST, whereas a higher correlation is obtained with segment length for RS. Stepwise regression *Equations 2, 3* and *4* obtained for each road segment show that, slope and segment length together yield higher correlation values. Therefore, the increase in segment area, which is in parallel to the increase in segment length, results in increased rill volume. Also, after a slope-based categorization of the road segments, the findings for erosion estimation increased significantly (*Fig. 4*). A wide scale of high slope values was observed for SCF, RC and ST, whereas the slope values of RS varied between 2-11% as per the standards for B-

type side roads. As a result of the narrow range of the slope values and similar erosion amounts corresponding to the slopes lower than 5%, the "RS < 5%" graph given in *Figure 4* exhibits a steeper slope as compared to the other graphs. This result is also indicative of the geometric increase in erosion amounts that occur on the road surface with increasing slope.
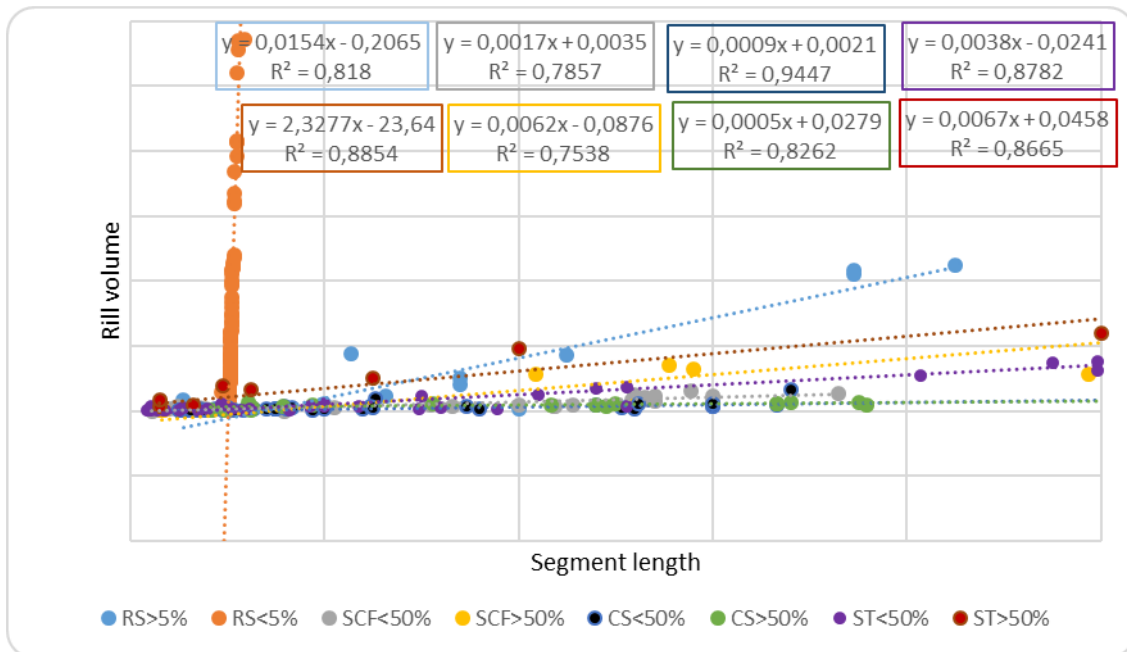

Figure 4. Rill volumes depending on segment lengths which are categorized by their slope

As also stated by Cao et al. (2014, 2015), rill volumes on short and steep road segments may be sometimes lower than those on low slope road segments. Accordingly, we also evaluated the rill volumes per unit segment area. According to the results of the correlation analysis between rill volumes per unit area and slope, the medium level correlation between slope and rill volume for RS and ST increased to a higher level (*Table 4*). As for SCF, the high level of correlation remained at a high level with a higher coefficient. On the contrary, the correlation level for RC with short and low slopes dropped to weak from medium, thus the effect of the slope factor on rill erosion is more evident for RS and ST. It is also revealed by the literature findings (Seutloali and Beckedahl, 2015; Anochie-Boateng et al., 2017; Safari et al., 2016; Thomaz and Ramos-Scharron, 2015; Yousefi et al., 2016) that, slope has a positive effect in the increase of rill erosion.

Table 4. Correlation of total and unit rill volumes for each road segment with slope

Road section	Rill Volume (m^3)	Unit Rill Volume (m^3/m^2)
RS	$p<2.2 \times 10^{-16}$; r=0.55; t=22.593; df=204	$p<2.20 \times 10^{-16}$; r=0.81; t=22.984; df=204
SCF	$p=3.67 \times 10^{-9}$; r=0.73; t=7.316; df=46	$p=1.33 \times 10^{-15}$; r=0.77; t=11.869; df=46
RC	$p=5.12 \times 10^{-8}$; r=0.57; t=6.039; df=77	$p=6.56 \times 10^{-5}$; r=0.43; t=4.222; df=77
ST	$p=9.60 \times 10^{-7}$; r=0.64; t=5.670; df=45	$p=1.71 \times 10^{-13}$; r=0.84; t=10.357; df=45

RS: Road surface, SCF: Sidecast fill, RC: Road cut, ST: Skid trail

In forestry, as the length of forest roads towards consumption centers increase, the length of inclined distances also increases. This in turn results in increased road-induced erosion risk and sediment yield. This situation is shown for each road segment in *Figure 4* that gives the correlation between segment length and rill volume for each slope category. *Table 5* gives the equations used in previous studies for estimation of erosion on unpaved forest roads. Variables such as L, S, $L^{1/2}$, S^2, LS, LS^2, $L^{1/2}S^2$ are used in these equations, which indicate that, segment length and slope are the right variables for estimation of rill erosion. As also shown in *Table 5*, the regression equations involving LS and LS^2 variables yielded the best results.

Table 5. *Comparison of the models and statistical results of segment length and slope-based rill erosion estimation studies with the research data*

Model	R^2	Reference	Model	R^2
E=aL+b	0.131	Luce et al. (1999)	E=0.02L+0.97	0.052[***]
E=aS-b	0.160[*]	Cao et al. (2014)	E=0.11S-0.38	0.221[***]
E=a$L^{1/2}$-b	0.790[**]	Cao et al. (2014)	E=0.64$L^{1/2}$-1.23	0.089[***]
E=aS^2+b	0.494[**] 0.110[*]	Luce et al. (1999) Cao et al. (2014)	E=1.38 $10^{-3}S^2$-0.13	0.449[***]
E=aLS+b	0.580[***] 0.180[**]	Luce et al. (1999) Madej (2001)	E=7.61 10^{-4}LS+0,66	0.244[***]
E=aLS^2+b	0.658[***]	Luce et al. (1999)	E=9.56 $10^{-6}LS^2$+0.62	0.498[***]
E=a$L^{1/2}$S+b	0.600[**]	Luce et al. (1999)	E=0.01$L^{1/2}$S+0.13	0.288[***]
E=a$L^{1/2}S^2$+b	0.629[**]	Luce et al. (1999)	E=1.28 10^{-4} $L^{1/2}S^2$+0.41	0.515[***]
E=aL+bS+c	0.543[**]	Luce et al. (1999)	E=2 10^{-3}L+0.11S-0.41	0.221[***]
E=aL+bS^2+c	0.577[***]	Luce et al. (1999)	E=-3.71 10^{-3}L+1.40 10^{-3} S^2+0.21	0.450[***]
E=aL+bLS^2+c	0.662[***]	Luce et al. (1999)	E=-2.45 10^{-2}L+1.13 $10^{-5}LS^2$+1.17	0.535[***]
E=aS+bLS^2+c	0.658[***]	Luce et al. (1999)	E=-1.35 10^{-2}S+1.01 $10^{-5}LS^2$+0.82	0.499[***]
E=aS^2+bLS^2+c	0.659[***]	Luce et al. (1999)	E=5.03 $10^{-4}S^2$+6.71 $10^{-6}LS^2$+0.37	0.513[***]
E=a$LS^{1.5}$+b	0.840[***]	Scharron (2010)	E=9.38 $10^{-5}LS^{1.5}$+0.59	0.378[***]
E=-a$LS^{0.13}$+b	0.830[**]	Scharron (2010)	E=0.02$LS^{0.13}$+0.93	0.067[***]

a, b, c: Coefficients, L: Segment length, S: Slope

As indicated by the results, more accurate findings are obtained through use of the values determined for unit area. The relationships between the maximum and average rill volumes and slope for each road segment are shown in *Figure 5*. Maximum values for all road sections except RC shows high correlation. Erosion estimations were performed using shear stress values and stream power sediment transport capacity theory and the results are shown in *Table 5*. These values were obtained using the data received from all road segments. The resulting findings for each road segment are given in *Table 6*, and the RMSE results of these models are expected to provide higher accuracy in erosion estimations.

Road length, slope and drainage area are the factors that affect erosion. Eroded volume is directly associated with road length which affects soil erosion on road segments by the combined effect of slope. L (segment length) and S (slope) variables together yield better results than single independent variables. This is clearly verified by *Equations 2, 3, 4* and *5,* and the equations given in *Table 6*. The models shown in *Table 6* involve the variables L, S and LS^2. These models yielded their best results for

RC, which features the shortest segment length, hence the lowest effectiveness. The models specified for RS and ST, which have similar segment lengths, exhibit similar mean error values.
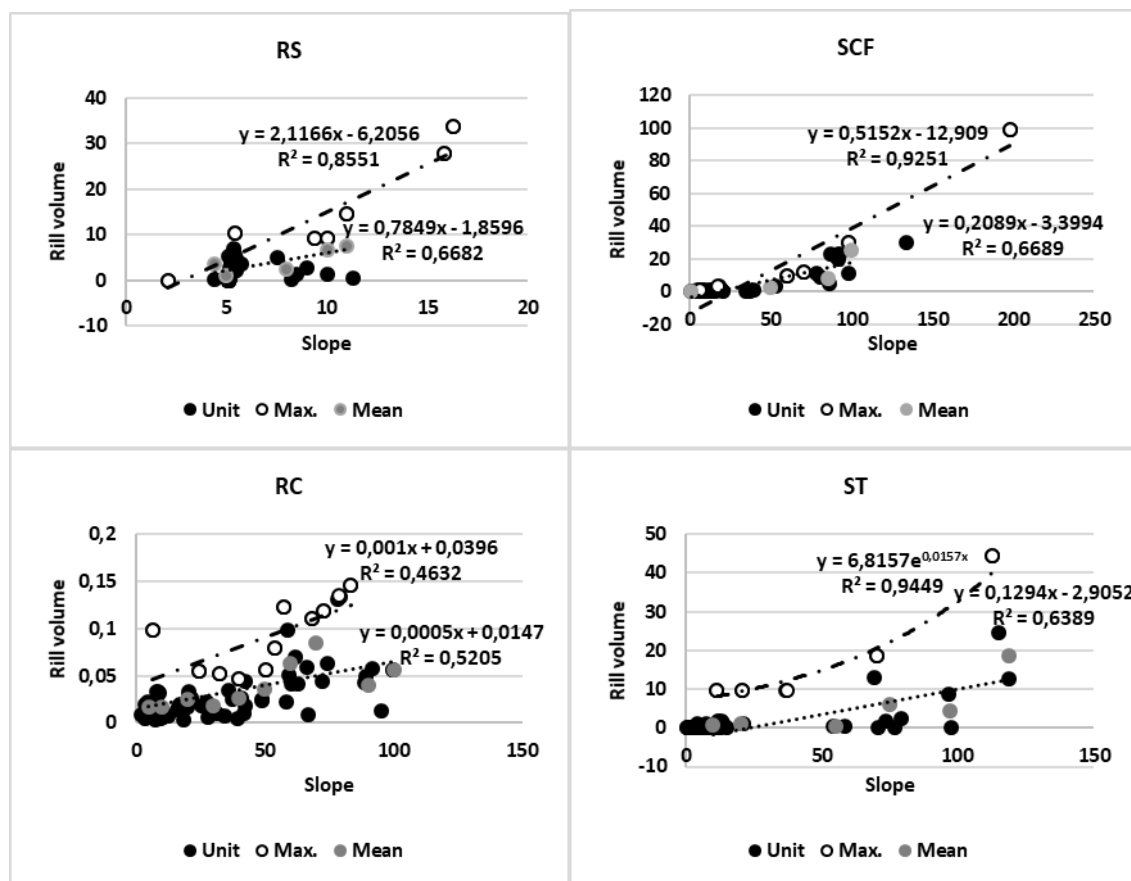

Figure 5. *Maximum and average values of rill volumes as a function of slope*

Table 6. *Comparison of erosion models for road segments given in Table 5*

Road section	Model	RMSE
RS	$E = 0.04\ L + 0.001\ LS^2 + 0.86$	0.16
SCF	$E = 1.71\ 10^{-3}\ S^2 + 4.25\ 10^{-6}\ LS^2 - 5.48\ 10^{-2}$	0.32
RC	$E = 8.36\ 10^{-4}\ S - 1.44\ 10^{-8}\ LS^2 + 8.62\ 10^{-3}$	0.03
ST	$E = 3.6\ 10^{-3}\ L + 2.86\ 10^{-7}\ LS^2 + 4.80\ 10^{-2}$	0.18
TOTAL	$E = -2.45\ 10^{-2}\ L + 1.13\ 10^{-5}\ LS^2 + 1.17$	1.45

RS: Road surface, SCF: Sidecast fill, RC: Road cut, ST: Skid trail, L: Segment length, S: Slope

Conclusion

In this study, rill erosion characteristics of different segments of unpaved forest roads were investigated in Arıt and Hasankadı Forest sub-districts of Bartın Forestry Directorate. According to the research results, the highest soil erosion rate occurs on road surface, which is followed by sidecast fill and skid trail with similar values, and the lowest erosion rate is observed on skid trail Segment length and the slope of the road

are the factors that affect erosion. As also reported in several other studies, more accurate statistical results are obtained via combined evaluation of segment length and slope. The findings of similar studies also indicate that better results can be obtained through inclusion of drainage area as a variable into the regression equations in estimation of rill erosion. On the other hand, drainage area slightly increases the accuracy of estimation equations particularly for unpaved forest roads. Inclined area had a negative effect on the observed road erosion especially on main roads. For such purposes, drainage area as a variable was excluded from the regression analysis as it is barely associated with the factors that affect road-induced erosion, although it resulted in 5, 10 and 8% increases in correlations for different types of forest roads. This brings about the necessity for evaluation of drainage areas' positive and negative contributions in addition to segment length and slope in future studies on determination of rill erosion. Also, similar studies should be performed on basins with more unpaved forest roads to widen the application extent of the findings obtained. In addition to the erosion rates on unpaved forest road segments, the sediment yield of other sections should also be determined for building road erosion models for basins.

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