# Evaluation of Different Best Management Practices for Erosion Control on Machine Operating Trails

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*Abstract*

*Ground-based mechanized forest operations often lead to increased runoff and soil loss on un-bound forest roads and machine operating trails, which in turn can impede the technical traf-ficability of machines and cause negative impacts on the environment. The aim of this study was to evaluate the effectiveness of three Best Management Practice (BMP) treatments used to control erosion occurring on machine operating trails. The treatments included water bar, water bar and hardwood brush (H-brush), and water bar and softwood brush (S-brush). For a more comprehensive assessment of both brush treatments, two levels of brush thickness were tested; 0.5 m and 1.0 m. Results indicate that the most effective BMP treatments were the water bar and softwood brush followed by the water bar and hardwood brush and finally the least effective was the water bar. The average runoff rates and soil loss from the machine operat-ing trails with the water bar treatment (52.64 l per plot, 8.49 g m$^{-2}$) were higher than runoff and soil loss at the trails protected with hardwood brush (23.75 l per plot, 4.5 g m$^{-2}$), and the trails protected by the hardwood brush had higher runoff and soil loss compared to trails covered by softwood brush (15.83 l per plot, 2.98 g m$^{-2}$). Furthermore, results of this study showed that regardless of the treatment, the amount of runoff and soil loss decreased consistently as the thickness of the brush mat increased. Overall, erosion control techniques similar to either H-brush or S-brush that provide direct soil coverage should be used for erosion control, and final selection should be based on costs, availability of material, or landowner objectives.*

*Keywords: runoff; brush, soil disturbance, soil protection, water bar, forest machines*

## 1. Introduction

Forest roads and machine operating trails can cause significant increases in surface runoff and sedi-ment yield, especially when bare soils are exposed to high machine traffic frequency or when the bearing capacity of a soil is exceeded and rutting occurs (Swift and Burns 1999, McBroom et al. 2008, Solgi et al. 2014). Therefore, most forestry Best Management Practices (BMPs) were developed with a focus on controlling erosion associated with transportation networks, in-cluding roads, wood landings, machine operating trails, and stream crossings (Aust and Blinn 2004, Anderson and Lockaby 2011). Typical BMPs for roads, machine operating trails, and landings include proper planning and location, control of longitudinal and transverse gradients, use of buffer areas, control of water, surfacing, road or trail closure to minimize soil

disturbance, and revegetation following harvesting (Swift 1985, Aust and Blinn 2004, Shepard 2006, Ice et al. 2010, Akbarimehr and Naghdi 2012a). These prac-tices are designed to achieve two significant objectives: control erosion at a harvest site and minimize the de-livery of sediment and pollutants to natural drainage lines (Wallbrink and Croke 2002).

Creation of water diversion structures to reduce runoff generation and sediment yield such as water bars can be a very effective sediment control method for limiting sediment delivery to adjacent areas (Wallbrink and Croke 2002). Water bars can be applied where other BMPs are less effective in controlling soil erosion and sediment discharge because of soil condi-tion, steep slope, and long slope length. In addition, water bars can be effectively adopted where the rain-fall amount is considerable. However, the utilization

of logging residues (brush) obtained during the processing phase of harvested trees in combination with water bars can be a successful combination to minimize soil erosion. Litschert and MacDonald (2009) recommended increasing water bar frequency and surface roughness on machine operating trails (e.g., litter, brush, and woody debris) in order to minimize the amount of sediment deposited into nearby streams.

Traffic on machine operating trails can alter hillslope hydrology by inducing compaction, which created less permeable soil surfaces that result in decreased infiltration and increased overland water flow, soil erosion, and sedimentation during rain events (Croke and Mockler 2001, Croke et al. 2001, Grace 2005, Jackson et al. 2002). The magnitude of environmental impacts caused by machine traffic is related to terrain gradient (Akbarimehr and Naghdi 2012a), traffic frequency of forest machines (Labelle and Jaeger 2011, Solgi et al. 2014), vegetation cover (Cerdà 2007, Lee et al. 2013), applied loads (Battiato et al. 2013), seasonality and rainfall intensity (Martínez-Zavala et al. 2008), soil texture (Pinard et al. 2000, Croke et al. 2001), and the time since construction (Fu et al. 2010). Morgan (1986) reported that soil erosion is affected by many factors, among them terrain gradient and vegetation cover have an important role on soil erosion.

Undisturbed area has minimal erosion and sedimentation due to good surface cover of trees and understory, which protects the soil surface from damaging storm energy (Grace 2002). Solgi et al. (2014) reported that, on control (undisturbed) plots, even the largest storm events did not generate runoff and sediment. Forest floor, woody debris, and brush increased surface roughness and provided dissipation of the energy associated with raindrop impact, which can dislodge soil particles (Wischmeier and Smith 1958).

Within a context of soil erosion on trails trafficked by forest machines, the specific objectives of this study were to:

⇒ evaluate the erosion control efficacy of three different machine operating trail BMPs (water bar only, water bar and hardwood brush, and water bar and softwood brush);

⇒ analyze the effectiveness of two brush mat thicknesses (0.5 m and 1.0 m) on the relative change of surface runoff and sediment yield.

## 2. Material and Methods

### 2.1 Study Area

This research was conducted from May to July 2016 in Shenrood forest, Guilan province, northern Iran between 36°13′ N and 36°15′ N and 53°10′ E and 53°15′ E. The area is predominantly covered by oriental beech (*Fagus orientalis* Lipsky) and common hornbeam (*Carpinus betulus* L.) stands. Brown forest soil was formed on unconsolidated limestone with a moderately deep profile. The soil was classified as Eutric Cambisols (FAO/UNESCO 1990), and Typic Eutrudepts (USDA Soil Taxonomy 1998). Soil collected at the research site from the 0–10 cm layer, was analyzed using the Bouyoucos hydrometer method and the texture was determined to be clay loam with a particle size distribution of 37% clay (<0.002 mm size), 38% silt (0.002–0.05 mm), and 25% sand (0.05–2 mm) along the machine operating trail. The average thickness of soil to the bedrock ranged from 60–70 cm. The elevation of the study sites ranged between approximately 900–1100 m above sea level with a northern aspect. The average annual rainfall recorded at the closest national weather station, located 20 km from the research area, is 1130 mm with a maximum mean monthly rainfall of 140 mm in October and a minimum rainfall of 25 mm in August. Based on historic weather data of the previous 50 years, the mean annual temperature is 16 °C, with lowest temperatures occurring in February. At the time of ground-based skidding, weather conditions were dry and warm with an average gravimetric soil moisture content of 19%. The soil had not been driven on before the experiment.

Harvesting operations were performed by chainsaws (felling and processing), followed by transportation of processed logs from the forest stand to roadside landings by a rubber-tired Timberjack 450C cable skidder. Due to the absence of trail protective treatments during trafficking with the cable skidder, no forest floor or litter material remained after skidding was completed.

### 2.2 Experimental Design

This study evaluated three BMP treatments used for erosion control on machine operating trails in the Hyrcanian forest, northern Iran. Prior to establishing the field test plots, ground-based skidding operations were performed over the target machine operating trails where machine traffic frequency was held constant at 21 loaded passes. BMP treatments consisted of water bar only (water bar), water bar and hardwood brush (H-brush), and water bar and softwood brush (S-brush). They were established in field plots on three machine operating trails with longitudinal gradients varying between 15–18% (Fig. 1). Both water bar and brush treatments for hardwood and softwood mats were further divided into two brush thickness levels defined as 0.5 m (light) and 1.0 m (heavy). Because of
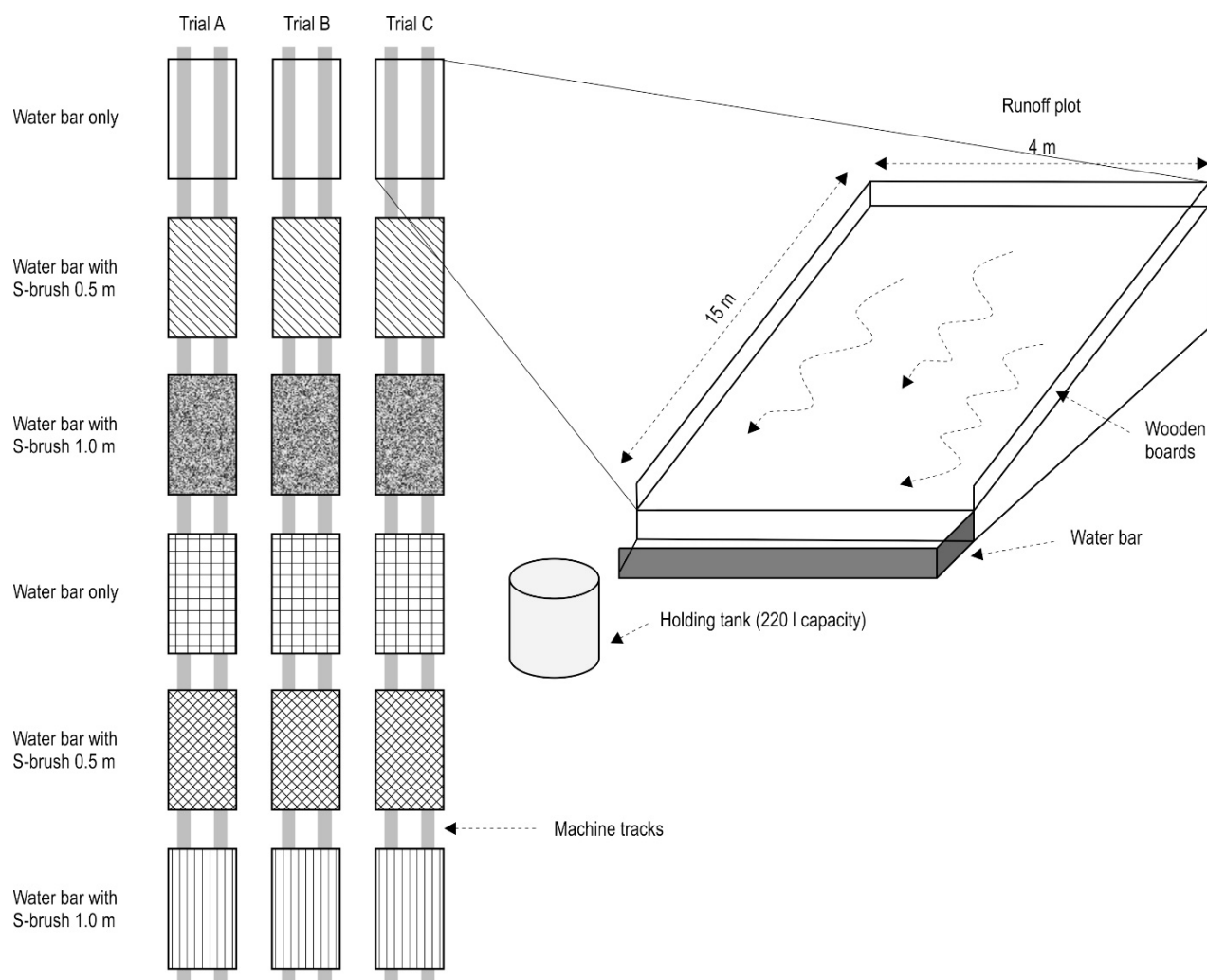
**Fig. 1** Experimental layout of field trials

the length of trail needed to establish all treatments, along with the associated possibilities of varying soil properties with extended spatial distribution, the water bar treatment was tested on two plots per machine operating trails. One plot was located with the hardwood plots and the other water bar plot was located with the softwood plots (Fig. 1). Therefore, a total of 18 runoff plots were installed that included a total of six combinations derived from three BMP treatments (water bar, H-brush, and S-brush) and two levels of brush mat thickness (0.5 m and 1.0 m) tested in triplicates. The H-brush and S-brush treatments consisted of the water bar plus an application of piled hardwood and softwood branches, which ranged from 2 to 15 cm in diameter at the large end and from 1.0 to 2.5 m in length. Hardwood brush was composed of branches of beech trees whereas softwood brush comprised branches of pine trees. To construct the needed brush

mats, branches originating from nearby felling operations were piled perpendicular to the axis of travel in each treatment plot until the target thickness (0.5 m or 1.0 m) was reached. Subsequently, the newly constructed brush mats were compacted by a John Deere 450E bulldozer to consolidate the branches, thus ensuring adequate ground contact (Wade et al. 2012).

Each treatment plot was 15 m long and 4 m wide, with a 5 m buffer zone between each plot to avoid interactions. Treatment plots were surrounded by wooden boards that were 30 cm in height and inserted 10 cm deep into the soil to control surface water movement from the inside to the outside of the plot area and vice-versa (Solgi et al. 2014). A water bar was constructed on the lower elevation side of each treatment plot so that all surface water runoff from inside the area could be collected in a holding tank with a capacity of 220 liters (Fig. 1). The inclination of a water bar

is important for slowing and diverting water from the machine operating trail and a slope of 2–4% is ideal. Therefore, water bars were installed with a 3% out-slope at a depth of 30–35 cm from the soil surface.

The sediment concentration within each treatment plot was determined after thorough mixing and bringing all the sediments into suspension and extracting a subsample of 1 liter of collected runoff material, and then using the drying and weighing method (Sadeghi et al. 2007). A collecting channel, made of sheet metal and covered with plastic or sheet metal to prevent direct entry of rainfall, was positioned at the downslope end of each plot. The volume of the surface runoff was computed after measuring the height of the water in the holding tanks. Samples were taken to the laboratory where the sediment was filtered and oven-dried at 105°C until a constant mass was obtained. (i.e., the drying and weighing method). For each rainfall event, we computed runoff volume and sediment loss from each plot. Holding tanks were emptied and cleaned after each rainfall and sampling event.

### 2.3 Statistical Analysis

One-way and two-way analysis of variances (ANOVA's) were used to assess the significance of observed differences in average runoff and soil loss in runoff plots from nine runoff events as a function of BMP treatments on different brush mat thickness and their interaction effects, respectively, at a significance level of $\alpha \leq 0.05$. Tukey's *HSD* test was used to compare the amount of runoff and soil loss among the three tested BMP treatments (main effects). All statistical calculations were performed in SPSS version 11.5.

## 3. Results and Discussion

Both hardwood and softwood branches used to create the brush mats were collected at the end of April 2016 from the harvested stands and had water content (percent of green mass) varying between 35 and 46%. The results showed that runoff rates and soil loss were significantly affected by BMP treatments as well as brush mat thickness, but the interactions of BMP treatment × mat thickness was not significant (Table 1).

The BMP treatments comprised of hardwood and softwood brush had significantly lower runoff and erosion rates compared to the water bar treatment (Table 2). Wade et al. (2012) conducted a similar study on machine operating trails and also reported the benefits of using H-brush and S-brush treatments to reduce erosion. When comparing both brush compositions (hardwood and softwood), results indicate that

**Table 1** *P* values based on analysis of variance of the effects of BMP treatments, brush mat thickness and the interaction between BMP treatments and brush mat thickness for runoff volume (liters) and soil loss (g m⁻²)

| Source of variable | d.f. | *p* Values* | |
|---|---|---|---|
| | | Runoff | Soil loss |
| BMP treatment | 2 | ≤ 0.005 | ≤ 0.005 |
| Mat thickness | 1 | ≤ 0.005 | ≤ 0.005 |
| BMP treatment × Mat thickness | 2 | 0.154 | 0.563 |

*P values less than 0.05 are given in bold

within a respective thickness level, softwood brush performed better through a lower runoff and erosion rate. When combining results from the two tested brush thickness levels, the average runoff rates and soil loss from the machine operating trails with the S-brush treatment (15.83 l per plot, 2.98 g m⁻²) were lower than the values measured at the trails with the H-brush treatment (23.75 l per plot, 4.5 g m⁻²), whereas the trails with the H-brush treatment had lower runoff and soil loss than the trail with the water bar treatment (52.64 l per plot, 8.49 g m⁻²). This is in agreement with findings reported by Sawyers et al. (2012) and Wade et al. (2012). Sawyers et al. (2012) also evaluated BMP treatments for machine operating trails and found the highest erosion rate with water bar only and lowest erosion rate with S-brush treatment. Wade et al. (2012) evaluated five BMP treatments (water bar only, water bar and grass seed (grass), water bar, grass seed, and straw mulch (mulch), water bar and piled hardwood brush, and water bar and piled softwood brush) on

**Table 2** Means (±std) of runoff volume (liters) and soil loss (g m⁻²) from different BMP treatments and brush mat thicknesses. H-brush, hardwood brush; S-brush, softwood brush

| | Mat thickness | BMP treatment | | |
|---|---|---|---|---|
| | m | Water bar | H-brush | S-brush |
| Runoff | 0.5 | 52.64±5.1^[Aa] | 30.93±3.6^[Ba] | 22.14±2.7^[Ca] |
| | 1 | 52.64±5.1^[Aa] | 16.57±2.4^[Bb] | 9.53±1.9^[Cb] |
| Soil loss | 0.5 | 8.49±1.4^[Aa] | 5.64±0.9^[Ba] | 4.03±0.6^[Ca] |
| | 1 | 8.49±1.4^[Aa] | 3.37±0.7^[Bb] | 1.94±0.4^[Cb] |

Note: Different letters within each treatment show significant differences (*P* < 0.05)

Capital case letters refer to the comparisons between the three BMP treatments for each mat thickness (row)

Lower case letters refer to the comparison between the two mat thickness levels in each BMP treatment separately (column)

**Table 3** Average reduction in runoff volume and soil loss (%) compared to water bar treatment. H-brush, hardwood brush; S-brush, softwood brush

| | Mat thickness | BMP treatment | |
| | m | H-brush | S-brush |
|---|---|---|---|
| Runoff | 0.5 | 41.2 | 57.9 |
| | 1 | 68.5 | 81.9 |
| Soil loss | 0.5 | 33.6 | 52.5 |
| | 1 | 60.3 | 77.1 |

machine operating trails in the Piedmont of Virginia and reported the highest erosion rate with water bar only and lowest erosion rate with the mulch treatment.

In our study, the H-brush and S-brush treatment reduced soil erosion (soil loss) by 60% and 77%, respectively when compared to the water bar treatment (Table 3). Sawyers et al. (2012) concluded that sediment production from surface erosion was reduced by 86% when a mulch treatment was applied to machine operating trails. Wade et al. (2012) reported 93% and 96% reductions in erosion when H-brush and S-brush treatments were applied to machine operating trails as compared to the water bar only. Grushecky et al. (2009) evaluated the effectiveness of fiber mats on soil erosion from machine operating trails as compared to water bars and seed and reported that the cover provided by the fiber mats reduced erosion by 88%. Our S-brush treatment provided partly similar erosion control results to those obtained with the fiber mats used by Grushecky et al. (2009), but the fiber mats would be considerably more expensive than brush, particularly if no biomass operations are intended for a harvest site.

The H-brush and S-brush treatments provided immediate surface cover of the treatment plot thereby protecting the bare soil from raindrop impacts, which minimized loosening of soil particles and reduced the velocity of surface runoff causing deposition of sediment. Jordán et al. (2010) reported that the BMP treatments increased the surface roughness and the interception of raindrops, which in turn delayed runoff generation. Puustinen et al. (2005) found that mulching contributed to decrease runoff flow and enhance water infiltration.

Our results showed that for a respective thickness level, S-brush treatment outperformed the H-brush treatment by providing better erosion control. Findings by Sawyers et al. (2012) and Wade et al. (2012) also support the effectiveness of S-brush mat for erosion control. Within a treatment plot, the S-brush treatment

had higher percentage of ground cover than what was visually noticed for the H-brush treatment. This likely occurred since the softwood brush was more easily broken apart by the bulldozer traffic than the hardwood brush, and since S-brush was also more consistent in leaf area as compared to H-brush. Those two main factors resulted in softwood brush having a more uniform contact with the soil, thus providing better overall coverage (Wade et al. 2012, Labelle and Jaeger 2015).

Irrespective of brush species composition, amounts of runoff and soil loss decreased consistently when mat thickness was increased (Table 2). With a lower mat thickness, the average runoff rates from the H-brush and S-brush treatments were reduced by 41.2% and 57.9%, respectively, when compared to the water bar treatment, while the reductions for the highest mat thickness were 68.5% and 81.9%, respectively (Table 3). Similarly, with the lower mat thickness, the average soil loss from the H-brush and S-brush treatments was reduced by 33.6% and 52.5%, respectively, when compared to the water bar treatment, while the reductions for the highest mat thickness were 60.3% and 77.1%, respectively (Table 3). The thickness of a brush mat placed on the soil can strongly affect runoff dynamics, and reduce runoff generation and soil loss (Rees et al. 2002, Findeling et al. 2003). Our findings support the use of combined water bars and brush mats, particularly the thicker 1.0 m mats, for effective protection against runoff and soil loss.

## 4. Conclusions

Research results indicate that forestry BMPs can effectively reduce sediment from ground-based mechanized forest operations. On relatively steep machine operating trails (15–18% longitudinal gradient), where soil erosion rates are normally very high, water bars alone may not provide sufficient erosion control. In this case, BMP techniques that enhance soil stability should be considered in combination with water bars. As such, the combination of the tested brush treatments with water bars were effective techniques in controlling erosion on machine operating trails. The effectiveness of the brush treatments are primarily linked to their added ground cover, which stabilizes the soil by providing protection from rainfall impact and reduction in overland flow velocity by increasing the surface roughness. Within test conditions and for a respective thickness level, softwood brush seemed to be more effective than hardwood brush.

Erosion rates were highest directly following skidding operations and the construction of the machine

operating trail. Since soils are highly susceptible to erosion after soil disturbance, especially during spring months, which generally experience higher intensity rain events, BMPs should be applied immediately after skidding is completed. The tested brush and water bar combination treatments offered the best protection against runoff and erosion rates. BMPs that provide sufficient soil cover, such as the brush treatments, should be used during these critical periods to prolong the technical performance of the trails for future use during re-entry and protect the surrounding environment from high erosion rates.

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