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Effectiveness of water diversion and erosion control structures on skid trails following timber harvesting

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ABSTRACT

Sediment in forested watersheds is produced primarily from highly disturbed areas such as skid trails. Forestry best management practices (BMPs) have been developed to minimize erosion and water quality problems, but the efficacies of various BMP options such as water bars are not well documented. The aim of this study was to evaluate the effects of different distances (slope lengths) between water diversion structures (water bars) on runoff volume and soil loss on different skid trail gradients on two soils with different textures. The treatments were located in an Iranian temperate forest and included combinations of three levels of trail gradient (<10%, 10–20% and >20%), four different distances between water bars (25, 50, 75, and 100 m), and two soil textures (clay loam and silt loam). Results showed that runoff volume increased curvilinearly and soil loss linearly with distances between water bars regardless of the soil texture and trail gradient. The greater distances on trail gradients >20% resulted in the highest amounts of runoff and soil loss; shorter distances on trail gradients <10% resulted in the lowest runoff and soil loss amount for the two tested soil textures. On the clay loam soil, 50 and 75 m were the most effective distances between water bars for trail gradients >20 and <20%, respectively. On the silt loam soil, 25 m and 50 m were the most effective distances between water bars for trail gradients >20 and <20%, respectively. The results of our study confirm that slope angle is a primary factor in controlling surface runoff and soil loss on skid trails and that soil texture becomes increasingly important as slope gradients become steeper. Therefore, reducing skid trail slope during construction skid trails is recommended to decrease surface runoff and soil loss in forest operations. Further, BMPs should consider soil texture in addition to slope gradient when recommending spacing between water bars.

1. Introduction

In forest stands, compaction following forest operations that employ large, heavy, powerful machinery is one of the main causes of soil disturbance (Brais, 2001; Rohand et al., 2004; Najafi et al., 2009; Naghdi et al., 2015). Skidding operations typically alter the physical soil structure and hydrology by increasing soil bulk density and soil strength, breaking down aggregates, decreasing porosity and pores sizes within the soil, and decreasing aeration and infiltration capacity, which can ultimately increase the potential for water runoff and erosion (Najafi et al., 2009; Solgi et al., 2014; Naghdi et al., 2015, 2016). These changes alter the way air and water move through the soil as well as the ability of roots to grow in the soil (Richard et al., 2001).

Although soil compaction can change many important soil physical properties, perhaps the most detrimental effect is a drastic reduction in hydraulic conductivity, which ultimately facilitates increased levels of soil erosion due to reduced infiltration, increased runoff and poor drainage (Solgi et al., 2014). The primary mechanism of increased soil erosion following compaction appears to be due to the noticeable increase in surface runoff (Greacen and Sands, 1980).

Natural soil erosion rates in forested areas tend to be very low, but erosion on cut and fill slopes and the road surface following road construction and small changes in soil compaction following skidding may enhance adverse consequences on runoff and erosion (Ramos-Scharrón and MacDonald, 2005; Solgi et al., 2014). Traffic on forest roads and ground skidding systems on skid trails are major sources of sediment generation in forest settings (Jusoff and Majid, 1996; Hartano et al., 2003). For example, in a water-

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shed in the southeast U.S., road prisms, i.e., road surface, ditches, and banks accounted for the vast majority (80%) of sediment delivery to streams and rivers (Van Lear et al., 1995). Soil erosion often follows enhanced physical impacts of raindrops on soil surfaces that can cause surface runoff (Froehlich, 1995) and enhanced sedimentation is the consequence of increased soil erosion and mass movements after heavy storms or prolonged rainy periods (Ziegler and Giambelluca, 1997; Gucinski et al., 2001; LaMarche and Lettenmaier, 2001; Jordan-Lopez et al., 2009).

Nonetheless, forest roads and skid trails are necessary to provide managers access to harvest areas (Akay et al., 2008). However, the standard to which roads are constructed differs and depends on the proposed end use, the amount of harvestable and marketable wood per unit area, and terrain conditions (Grace and Clinton, 2007). Forest roads are typically built to a higher standard than skid trails, including regular use of gravel for road surfaces, crowning, ditches and culverts, and water bars typically lacking in skid trails (Stringer et al., 1998; Grace and Clinton, 2007; NRCS, 2014). Skid trails on the other hand are typically cleared areas within the forest (NRCS, 2014) and are repeatedly used by machinery to carry harvested trees to the landing/main roads during the harvesting operation, leading to high frequencies of machinery traffic over the same trail (Zenner et al., 2007). Skid trails are typically located in areas where proper road construction operations cannot be performed; thus they have the potential to contribute large amounts of sediment to waterways until the trail is properly protected after termination of the skidding operations (Grace and Clinton, 2007). Roads of minimum or below standard as well as skid trails often accelerate soil erosion losses over time or lead to sudden mass failures that can introduce large quantities of sediment into the waterways and reduce water quality (Patric, 1976; Yoho, 1980; Swift, 1985; Binkley and Brown, 1993; Grace et al., 1998; Grace, 2002, 2005; Grace and Clinton, 2007). In fact, most of the erosion features in forests connected to stream channels may actually originate from skid trails (Litschert and MacDonald, 2009) due to altered subsurface hydrology and decreased hydraulic conductivity on compacted and less permeable surfaces that can result in erosion during rain events (Croke et al., 2001; Croke and Mockler, 2001; Jackson et al., 2005; Grace, 2005).

The severity of adverse impacts of skid trails is further related to the slope gradient (Akbarimehr and Naghdi, 2012a,b), traffic volume (Akay et al., 2008; Solgi et al., 2014), vegetation cover (Cerdà, 2007; Lee et al., 2013), mechanical pressure (Battiato et al., 2013), road surfacing material (Akay et al., 2008), seasonality and rainfall intensity (Martínez-Zavala et al., 2008), soil texture (Croke et al., 2001), and the time since construction of the skid trail (Fu et al., 2010). Although soil erosion is affected by many factors, the soil type/texture, the gradient of the slope, and the presence/absence of ground vegetation seem to have pivotal roles in determining soil erodibility potential (Morgan, 1986). Soil texture determines the susceptibility of a soil to erosion in that erosion rates can differ among various soil types under the same conditions of rainfall intensities, slope gradients and amounts of vegetation cover (Hussein et al., 2007; Mohamadi and Kavian, 2015). The slope gradient plays an important role in soil loss (Jordan-Lopez et al., 2009), because runoff velocity can increase with the increasing slope gradients and lead to excessive soil erosion/loss (Koulouri and Giourga, 2007; Kateb et al., 2013). Indeed, sediment yields per unit area of machine operating trail strongly depend on the gradient of the trail (Akbarimehr and Naghdi, 2012a), while in contrast even the largest storm events do not generate any runoff and sediment on flat control plots (Solgi et al., 2014).

To minimize runoff and soil erosion, Best management practices (BMPs) typically recommend implementation of soil erosion control practices designed to minimize the delivery of sediment and pollutants to natural drainage lines (Wallbrink and Croke, 2002). While it is customary to design water diversion structures for forest roads, the importance of skid trails as sources of runoff and sediments has not been sufficiently considered (Martínez-Zavala et al., 2008), even though machine operating trails may have greater potential for erosion due to less elaborate water control structures (Wear et al., 2013). BMPs often recommend water bars as diversion structures that are quick and easy to construct, particularly in places where other best management practices such as ground cover by slash, vegetation, or similar treatments are deemed ineffective for controlling soil erosion and sediment discharge because of soil condition, slope gradient, slope length, and costs (Stringer et al., 1998; Wade et al., 2012). Water bars are intended to slow the speed of flowing water and divert flowing water from a road or retired skid trail to adjacent forest land (Miller, 2006) and can be effectively adopted in areas with large rainfall amounts (Wade et al., 2012). As a consequence, water bars are a very effective sediment control strategy capable of reducing runoff generation and limiting sediment yield and delivery to adjacent areas (Wallbrink and Croke, 2002).

Although water bars seem to be a particularly beneficial instrument for erosion control on retired skid trails in mountainous forests that exhibit steep slopes and road gradients (Akbarimehr and Naghdi, 2012a,b), there is no consensus on recommended distances of water bars among different BMPs (Copstead et al., 2003). Further, recommended maximum distances between water bars do not depend on soil texture (NRCS, 2014), even though soil texture is a major determinant of soil erodibility potential (Morgan, 1986). To expand research of a recent study that determined the distances between water bars that minimized runoff and soil loss for a clay-loam soil (Akbarimehr and Naghdi, 2012b), this study aims to determine the distances between water bars that minimize runoff and soil loss for skid trails on two different soil textures and three different slope gradients. Thus, the specific aims of this study were to (*i*) quantify the amount of runoff and soil loss generated at different distances between water bars on clay loam and silt loam on three slope gradient classes, (*ii*) determine potential interactions among soil textures, slope gradient, and distances, (*iii*) identify the distances between water diversions on skid trails that minimize runoff and soil loss for soils of different textures and for different slope gradients, and (*iv*) discuss the relationship between soil texture and soil loss.

2. Material and methods

2.1. Study area

This research was conducted between November 2015 and January 2016 in Shenrood forest, Guilan province, northern Iran (36°13′N and 36°15′N and 53°10′E and 53°15′E) (Fig. 1). The area is predominantly covered by stands of oriental beech (*Fagus orientalis* Lipsky) and common hornbeam (*Carpinus betulus*) with canopy cover of 0.81 (Site 1) and 0.79 (Site 2). The area is characterized by brown forest soils formed on unconsolidated limestone. Soils have a moderately deep profile and are classified as Eutric Cambisols (FAO/UNESCO, 1990) and Typic Eutrudepts (USDA Soil Taxonomy, 1998). Soil textures in the studied skid trails were determined based on particle size analysis using the Bouyoucos hydrometer method (Kalra and Maynard, 1991) and classified as a clay loam (Site 1) and silt loam (Site 2) soil (Table 1). The average depth of the soil to bedrock ranged between 60 cm (Site 1) and 70 cm (Site 2). The elevations of the two study sites were approximately 900–1100 m above sea level with a northerly 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