Effectiveness of sawdust and straw mulching on postharvest runoff and soil erosion of a skid trail in a mixed forest

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ARTICLE INFO

Keywords:
Skid trails
Runoff
Sediment yield
Mulching
Sawdust
Straw

ABSTRACT

Loss of vegetation cover by forest harvesting has increased the average surface runoff volume and sediment yield in the Hyrcanian forest in Iran. Hence, treatments are needed to mitigate the effects of skidding operations on hydrological characteristics and sediment delivery into streams. The present study evaluated the efficacy of straw and sawdust mulches in reducing soil erosion relative to untreated control plots in a severely compacted loam soil area in the Hyrcanian forest during the first year after harvesting. Immediately after skidding operations, triplicate skid trail plots received straw mulch (16.5 kg m⁻²) sawdust mulch (2.8 kg m⁻²) or were left untreated for the control plots (8 m²). The experimental design was completely randomized; plots were randomly assigned to treatment, season, and leafless and leafed periods. The results of generalized linear modeling showed that season and treatment significantly affected the amount of runoff and sediment. Runoff was significantly lower in the summer than in the other seasons. Applying straw mulch to the skid trail decreased runoff by 36.5%, and sawdust mulch decreased runoff by 72.8% compared with the control. The straw and the sawdust mulch also decreased sediment yield by 51.9% and 94.9%, respectively. A regression analysis revealed that the runoff response to rainfall for all the treatments was linear. Also, the total measured runoff in all seasons after the straw and the sawdust mulch was less than the runoff of the control plots. However, the measured runoff in the leafless period was greater than in the leafed period. In the straw and the sawdust mulch, measured runoff in the leafless period was 91.7% and 89.8% of the total runoff, respectively. In the straw and sawdust treatment, 99.4% and 98.4%, respectively, of the sediment occurred in the leafless period. Covering the bare mineral, compacted soil on skid trails thus greatly reduces surface runoff and sediment yield.

1. Introduction

Since forest soils have high organic matter, low bulk density, high porosity, high permeability, and low resistance to penetration, they are sensitive to soil compaction (Ampoorter et al., 2007; Jourgholami et al., 2014) and shear stress (Horn et al., 2007; Eliasson and Wasterlund, 2007), especially from logging activities. A mechanical load (e.g., skidding machine) applied to the soil changes the soil aggregate and distribution; compaction and shear stresses cause the soil particles to merge, increasing soil bulk density (Grace et al., 2006; Cambi et al., 2015). The most important effect of this reduced permeability of compacted soils is runoff, that reduces the soil water balance and often leads to soil erosion (Croke et al., 1999, 2001; Kozlowski, 1999; Cristan et al., 2016; Ashcroft et al., 2017).

Logging operations also cause wheel ruts, especially in wet soils and on steep trails where water can create gullies and erode the land (Christopher and Visser, 2007; Cambi et al., 2017). Skid trails, like forest roads, are thus a major source of sediments (Hartanto et al., 2003; Stuart and Edwards, 2006; Christopher and Visser, 2007; Hotta et al., 2007; Smith et al., 2011; Holz et al., 2015; Wagenbrenner et al., 2015). The loss of vegetation cover after forest harvesting also increases the volume of surface runoff and sediments (Hartanto et al., 2003; Brown et al., 2005; Moore and Wondzell, 2005; Wade et al., 2012; Webb et al., 2012; Ide et al., 2013; Holz et al., 2015). Hence, timber harvesting operations are considered as nonpoint source pollution (NPSP) (Wade et al., 2012; Cristan et al., 2016).

Various mulches (material such as straw, leaves, plastic film, or loose soil that is spread on the surface of the soil to protect the soil and plant roots) have also been applied to control and mitigate surface runoff and sediment after wildfires (Wagenbrenner et al., 2006; Robichaud et al., 2008, 2009, 2016; Dodson and Peterson, 2010; Prats et al., 2012; Santana et al., 2014; Diaz-Ravinha et al., 2015; Vega et al., 2015). Agricultural straw, seeding herbaceous plant or shrub seed alone or in combination with other postwildfire rehabilitation activities, geotextiles, hydromulches and dry mulches made from forest materials (e.g., wood strands, wood chips, or wood shreds) have been tested and
in some cases applied as postfire hillside treatments in the several studies (Peppin et al., 2010; Robichaud et al., 2013; Prats et al., 2014; Vega et al., 2014; Sadeghi et al., 2015; Wagenbrenner et al., 2015; Fernández and Vega, 2016a,b). Although neither the types of effects nor the intensities of the disturbance of wildfires are comparable to those of ground-based logging, but in each case, removing the litter layer and increasing soil compaction eventually leads to decreased water permeability and increased runoff and sediment. In a study of postfire salvage logging, Wagenbrenner et al. (2015) found that sediment production from burned soils in skidder trail plots was 10–100 times greater than in the undisturbed control plots.

Forestry best management practices (BMPs), including operations such as log landings, skid trails, stream crossings, and site preparation (Cristan et al., 2016), have helped decrease surface runoff and sediment in streams and rivers (Stuart and Edwards, 2006; Wade et al., 2012; Sawyers et al., 2012). Amending skid trails with slash (Wagenbrenner et al., 2015), adding fiber to skid roads (Grushecky et al., 2009), mulching just after a fire (Wade, 2010; Fernandez and Vega, 2016a,b; Fernandez and Vega, 2016a,b), scattering slash and litter (Fernandez et al., 2004; McIver and McNeil, 2006), rapidly applying mulch (Sadeghi et al., 2015; Prats et al., 2016a,b), using BMPs techniques (Wade, 2010; Nolan et al., 2015; Cristan et al., 2016), and installing waterbars and/or applying slash, mulch, or a combination of mulching and seeding (Cristan et al., 2016) have been recommended. Additionally, Sawyers et al. (2012) evaluated the erosion control effectiveness of five overland skid trail closure techniques and found that combining water bar installation with seeding and mulching was most effective for reducing erosion (3.29 Mg ha\(^{-1}\) yr\(^{-1}\)), followed by water bar plus mulching with hardwood slash (5.08 Mg ha\(^{-1}\) yr\(^{-1}\)). When Wade et al. (2012) examined five BMPs for bladed skid trail closures to control erosion in the Piedmont region of Virginia in the United States, the water bar was the most effective at controlling erosion (137.7 t of sediment ha\(^{-1}\) yr\(^{-1}\)). Wear et al. (2013) applied skid trail stream crossing BMP including slash, mulch, grass seed, silt fence and mulch plus grass seed. Results showed that the most effective methods for reducing the amount of sediment entering the stream was the slash treatment (62.7% reduction), followed by the mulch treatment (15.8% reduction), and finally the mulch + silt fence treatment (10.5% reduction).
reduction). Also, Litschert and MacDonald (2009) concluded that sediment yield from timber harvests may be reduced by locating skid trails away from streams, maintaining high surface roughness downslope of water bars, and decommissioning skid trails.

In the Hycranian forests in northern Iran, timber is extracted by wheeled and crawler skidders, which disturb the soil, increase soil bulk density, and reduce soil porosity, resulting in surface runoff and soil erosion (Jourgholami and Majnousian, 2013; Jourgholami et al., 2014). Also, falling leaves and loss of canopy cover from October to April (leafless period), which coincides with the highest erosive rainfall, are important factors in the increased runoff. However, most of the previous research was carried out in the coniferous or evergreen forest stand and a few studies have been conducted in deciduous forests. In addition, many studies in the deciduous forests were done during the leafed or growing season; very few were examined both the leafed and the leafless periods (Herbst et al., 2008; Gerrits et al., 2010; Hoseini et al., 2011).

Additionally, when soil is disturbed before the leaves fall and canopy cover is lost, less rain is intercepted, intensifying the effects of soil disturbance and loss of litter layer. Although the operational plan guideline of the Forest, Rangeland and Watershed Organization (Iran) lists forestry BMPs to reduce runoff and sediment after logging, the effectiveness of these treatments in reducing runoff and sediment has not actually been studied. One of the most important emergency treatments for skid trails upon completion of logging operations is the application of mulch, including straw and sawdust, but no studies have examined the efficacy of straw and sawdust in mitigating the effects of harvesting operations on skid trails in the natural conditions in the Hycranian forest. The aim of this study is to evaluate the ability of the straw and the sawdust mulches to reduce soil erosion relative to untreated control plots immediately after skidding operations on severely compacted soil of a skid trail in the Hycranian forest.

2. Material and methods

2.1. Site description

The research was carried out in compartment no. 313 of the Gorazbon District in the Kheyrud Forest in the Hycranian forest of northern Iran (Fig. 1). This compartment ranges in altitude from 1110 to 1290 m above sea level and lies on a southern aspect. Average rainfall ranges from 1150 to 1260 mm yr⁻¹ and is heaviest in summer and autumn. Average daily temperatures range from a few degrees below 0 °C in December, January, and February to +25 °C during the summer. Soils are classified as well-drained forest brown soils (Alfisols) with a soil texture ranging from silt loam to loamy. The study area is a combination of group selection and single tree selection. The skidding operation took place in May 2015 using a 4WD Timberjack 450C rubber-tired skidder.

2.2. Experimental design

Immediately after the skidding operation, nine runoff plots were established in the study area. Treatments were applied to each of three skid trials selected, with three plots per trail. Hence, three treatments were done in triplicate: no treatment (control), sawdust mulch, and rice straw mulch. The hardwood forest residue treatments consisted of an application of hardwood sawdust, with diameters ranging from 1 to 5 mm and lengths from 0.5 to 14 cm and total mass of 16.5 kg m⁻² to cover approximately 100% of the plot surface (Prats et al., 2012; Fernández and Vega, 2016b). The sawdust was made from beech and hornbeam, the dominant species in the study area. Straw was applied after the skidding operation at a rate that initially gave 100% coverage (2.8 kg per m²) (Vega et al., 2014; Wagenbrenner et al., 2015; Fernández and Vega, 2016a,b). The rice straw averaged 4–17 cm long and 4–6 mm thick.

The skid trails selected for the study are similar in terms of slope, aspect, soils, area, climate and vegetation and adjacent to each other. Sample plots, established on the skid trails after the skidding operation, were characterized by bare, compacted soil (0–10 cm depth) lacking a litter layer and organic debris. The slope class included trail sections with 15–24% slope.

In the study area, the forest has both a deciduous, leafless period and a growing, leafed period, so to study the effect of leaflessness on changes in runoff and sediment yield, two treatment periods were also evaluated: a leafless period (October 30, 2015–April 16, 2016) and leafed period (from April 16, 2016 to October 30, 2017). In each sample plot, six variables were measured: canopy cover, litter depth, bulk density, organic matter, pH, and soil particle size distribution (Table 1). Bulk density was measured using a metal ring pressed into the soil (Jourgholami et al., 2014).

2.3. Rainfall, runoff and sediment measurements

The study was carried out from July 18, 2015 to April 16, 2016. Three 8-m² microplots (4 × 2 m) area were set up for each slope class on the skid trail and for the treatment area to measure surface water runoff and sediment (Fig. 1). Each plot was bordered by strips of a metal sheet placed to a depth of 20 cm and about 15 cm above the soil surface to prevent input from the adjacent area. Plastic pipe was used to convey the runoff water to a 0.1 m³ tank which placed in dug hole at the bottom of the plot. After each rainfall, the runoff volume was measured using a graduated cylinder, and the runoff samples were filtered, oven-dried at 105 °C, and weighed to determine the suspended sediment yield. Two standard rain gauges were used to measure the amount of rainfall at the skid trails and the control area; the rainfall gauges were located less than 100 m away from the runoff plots. Rainfall collected was measured after each rainfall event; 56 rainy days and 23 runoff events were registered during the study.

2.4. Statistical analyses

The experimental design was a completely randomized design where plots were randomly assigned to the treatment and season. Generalized linear modeling (GLM, two-way analysis of variance) was applied to relate runoff and sediment responses to treatment and season. Since no departure of the data from a normal distribution was determined by the Kolmogorov-Smirnov test (α = 0.05), standard parametric analyses were carried out. Homogeneity of variance among

### Table 1

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Bulk density (g cm⁻³)</th>
<th>Litter depth (cm)</th>
<th>Canopy cover (%)</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>pH</th>
<th>Organic matter (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1.31 fi</td>
<td>0.00 fi</td>
<td>76 fi</td>
<td>44.4 fi</td>
<td>35.2 fi</td>
<td>20.4 fi</td>
<td>5.6 fi</td>
<td>2.9 fi</td>
</tr>
<tr>
<td>Straw</td>
<td>1.29 fi</td>
<td>0.00 fi</td>
<td>73 fi</td>
<td>43.3 fi</td>
<td>38.1 fi</td>
<td>18.6 fi</td>
<td>5.3 fi</td>
<td>3.1 fi</td>
</tr>
<tr>
<td>Sawdust</td>
<td>1.35 fi</td>
<td>0.00 fi</td>
<td>72 fi</td>
<td>39.7 fi</td>
<td>37.8 fi</td>
<td>22.5 fi</td>
<td>5.5 fi</td>
<td>3.3 fi</td>
</tr>
</tbody>
</table>

Note: Different letters indicate statistically significant differences (α ≤ 0.05) between group means using Duncan’s test (P < 0.05).
treatments was verified by Levene’s test (α = 0.01). Post hoc comparisons of the season and the treatment group means were performed using Duncan’s multiple range test with a 95% confidence level. Treatment effects were considered statistically significant when $P \leq 0.05$. The regression analysis was carried out between runoff and sediment as the dependent variable to the rainfall and also between sediment as the independent variable to the runoff for the three treatments (control, straw and sawdust), and both leafless and leafed period. SPSS (release 17.0; SPSS, Chicago, IL, USA) statistical package was used for analyses.

3. Results

3.1. Soil properties

The soil bulk density, litter depth and cover canopy for the two studied sites are summarized in Table 1. Since all the plots were located on skid trails, bulk density did not differ significantly ($P \leq 0.05$) among treatments. Forest floor litter depth, considered the single most important indicator of soil quality, did not differ significantly among the three study sites, nor did canopy cover for the three study sites. The amount of sand, clay and silt particles did not differ among treatments. Forest floor litter depth, considered the single most important indicator of soil quality, did not differ significantly among the three study sites, nor did pH or the amount of organic matter.

3.2. Runoff

Fig. 2 shows the mean daily rainfall recorded in the study area. In total, 56 rainfall days were recorded, with 1217 mm total rainfall during the study in the study area. The average daily rainfall in the region was 42.7 mm. Most rainfall occurred in autumn (666.8 mm). The results of the GLM showed that season and treatment significantly affected the amount of runoff, but the season × treatment interaction did not (Table 2).

Runoff was lowest in the summer (0.19 mm) and differed significantly from that in each of the other seasons, but did not differ among spring, autumn and winter (Table 3).

Both treatments significantly reduced runoff. On average, the most runoff was measured in the control plot, and the straw mulch treatment of the skid trail decreased runoff by 36.5% (Table 3). The plot with the sawdust mulch had the least runoff at 0.44 mm and the sawdust mulch decreased runoff by 72.8% (Table 3).

In all seasons, the sawdust mulch decreased runoff the most, followed by the straw mulch treatment. The highest runoff (2.18 mm) occurred in winter and the control plot, and skid trails with the sawdust and the straw in the summer had the least runoff at 0.07 and 0.16 mm, respectively (Fig. 3).

The results showed that the total measured runoff for all seasons combined (95.56 mm) in the control plots were greater than after the straw and the sawdust mulching. The total runoff of the straw treatment was 35.03% lower than in the control plot (Fig. 4). Even better, the sawdust mulch treatment decreased runoff by 72.6%. However, the measured runoff in the control plots in the leafless period (86.94 mm) was higher than in the leafed period (8.6 mm).

In the control plots, the runoff during the leafless period was 91% (86.94 mm) of the total runoff (95.56 mm) (Fig. 4a). Similarly for the straw mulch, 91.7% (56.94 mm) of the total runoff (62.08 mm) (Fig. 4b), and for the sawdust mulch, 91.7% (23.48 mm) of the total runoff (26.15 mm) occurred in the leafless period (Fig. 4c). In other word, the runoff for the control plots, the straw, and the sawdust treated trail in the leafed period were 8.61, 5.14, and 2.67 mm, respectively. During the leafless period, the runoff in the straw and the sawdust plots decreased by 34.5% (29.99 mm) and 72.9% (63.46 mm), respectively. However, the runoff for the straw and the sawdust treated trail in the leafed period decreased by 40.3% (3.48 mm) and 68.9% (5.94 mm), respectively, compared to the control plot.

Note: Different letters after means within each season and treatment indicate significant differences by Duncan’s test ($P < 0.05$).
3.3. Sediment yields

The GLM results showed that the season, treatment and their interaction significantly affected sediment levels (Table 2). Results showed that season had a significant effect on sediment levels, average sediment levels in summer (0.001 kg m$^{-2}$) were significantly lower than the levels in the other seasons (Table 3). As found for runoff levels, Duncan’s tests didn’t detect significant differences among spring, autumn and winter for sediment yield, although the yields were highest.

Results showed that the treatments significantly affected sediment yields, with yields from the control plot that were 2–20 times higher (0.079 kg m$^{-2}$) than from the mulched plots (straw: 0.038 kg m$^{-2}$, sawdust: 0.004 kg m$^{-2}$). The straw and sawdust mulches thus significantly decreased sediment yield by 51.9% and 94.9%, respectively (Table 3).

Sediment was significantly affected by a season × treatment interaction (Fig. 5). The control plot in the autumn had the highest sediment (0.135 kg m$^{-2}$), followed by the control plot in winter, and the control and straw treatment in spring; however, the yield from the control plot and from the straw-mulched plot in spring did not differ significantly. The yield from the straw mulch plot in winter and autumn was the next highest. The sediment from the plot with straw mulch in the summer was 0.0003 kg m$^{-2}$ and 0.00006 kg m$^{-2}$ from the sawdust-mulched plot, the lowest of all the treatments (Fig. 5).

The total sediment yield from the control plot during the study period was 5.408 kg m$^{-2}$, while the sediment from the straw-mulched plot was 2.12 kg m$^{-2}$ and 0.26 kg m$^{-2}$ from the sawdust mulched (Fig. 6). Thus, the yield from straw and the sawdust plots was 60.8% and 95.2% lower, respectively than from the control plot. On the other hand, the highest sediment level in the control plot was 5.34 kg m$^{-2}$ during the leafless period, and 1.3% of total sediment yield occurred...
during the leafed period (Fig. 6a). Also in the straw treatment, 99.4% of the sediment occurred in the leafless period and only 0.6% of the sediment was lost in the leafed period (Fig. 6b). Similarly for the sawdust mulch, 98.4% of the total sediment was produced during the leafless period, with only 1.6% during the leafed period (Fig. 6c).

3.4. Leafed and leafless period, runoff, and sediment level

The runoff and sediment level were significantly higher in the control and straw mulch during the leafless period (Table 4). However, there were no significant differences among runoff or sediment levels among treatments during the leafed period (Table 4). During the leafless period, the straw and sawdust mulch decreased runoff by 34.5% and 72.9% and sediment yield by 61% and 95.2%, respectively (Table 4).

A regression analysis of rainfall and runoff revealed that the runoff response to rainfall for the control plots, the straw mulch and the sawdust mulches was linear and statistically significant (Fig. 7). However, the required rainfall depth for the start of runoff during the leafless period for the control plot was lower than for the straw and the sawdust plots. However, the rainfall response to runoff for all treatments during the leafed period was linear, which was statistically significant. However, the rainfall depth for the start of runoff during the leafed period was higher than for the same treatments when leaves were absent (Fig. 7b).

A regression analysis between rainfall and sediment levels revealed a statistically significant linear response of sediment to runoff for the control plot, the straw and the sawdust mulches was linear and statistically significant (Fig. 7c). However, the rainfall depth for sediment yield in the leafless period in the control plot was lower than for straw and sawdust. Further, sediment responses to rainfall for all treatments in the leafed period were linear and statistically significant (Fig. 7d). Likewise, the rainfall depth for sediment yield from the sawdust mulch treatment (20 mm) and the straw mulch (14 mm) was higher than the rainfall depth of the control plot (9 mm).

Table 4
Effects of canopy cover and treatment on mean runoff and sediment.

<table>
<thead>
<tr>
<th>Canopy cover</th>
<th>Treatment</th>
<th>Runoff (mm)</th>
<th>Sediment (kg m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leafed period</td>
<td>Control</td>
<td>0.4307b</td>
<td>0.0033b</td>
</tr>
<tr>
<td></td>
<td>Straw</td>
<td>0.2569b</td>
<td>0.0005b</td>
</tr>
<tr>
<td></td>
<td>Sawdust</td>
<td>0.1336b</td>
<td>0.0002b</td>
</tr>
<tr>
<td>Leafless period</td>
<td>Control</td>
<td>2.4151a</td>
<td>0.1504a</td>
</tr>
<tr>
<td></td>
<td>Straw</td>
<td>1.5618a</td>
<td>0.0586a</td>
</tr>
<tr>
<td></td>
<td>Sawdust</td>
<td>0.6522b</td>
<td>0.0072b</td>
</tr>
</tbody>
</table>

Note: Different letters after means within each canopy cover and treatment indicate significant differences by Duncan’s test ($P < 0.05$).
during the leafless period for the control, straw and sawdust mulch were 0.702, 0.823 and 0.721, respectively, and 70.2%, 82.3% and 72.1% of the variation around the mean for runoff in the control plot, straw and sawdust mulch, respectively, can be explained by rainfall (Fig. 7a and b). In the leafless period, $R^2$ (coefficient of determination) between sediment and rainfall for the control, straw and sawdust mulch was 0.721, 0.746 and 0.421, respectively; thus, roughly 72.1%, 74.6% and 42.1% of the variance in the response variable (sediment) can be explained by the predictor variable (rainfall) (Fig. 7c and d).

A regression analysis between runoff and sediment revealed that a significant change in the linear sediment response to runoff for the control plot, the straw and the sawdust mulch for both the leafless period and the leafed period (Fig. 8a and b). In any specific amount of the runoff, sediment yield from the control plot was higher than from the straw treatment, and sediment level from the straw treatment was higher than from the sawdust treatment. In the leafed period, not only did sediment level decrease as runoff dropped sharply, but also the sediment yield was lower than in the leafless period (Fig. 8a and b).

In the leafless period, $R^2$ between sediment and runoff for the control, straw and sawdust mulch was 0.889, 0.855 and 0.812, respectively; roughly 88.9%, 85.5% and 81.2% of the variance in the sediment response can be explained by the runoff (Fig. 8a and b).

4. Discussion

In the present study on mulching treatments of compacted skid trail plots to reduce runoff and sediment from the sites, the highest values for bulk density of the soil, which corresponded to the lowest porosity percentages, were recorded in skid trails. Ground-based skidding operations strongly affected runoff and the sediment. As others have...
found, removing the litter layer and organic matter and increasing soil bulk density leads to greater runoff and sediment (Grace et al., 2006; Ampoorter et al., 2007; Jourgholami et al., 2014; Cambi et al., 2015). Beyond the canopy cover, the next layer of protection against rain is the litter layer. Forest floor litter layer not only helps protect soil against splashing and the kinetic energy of throughfall, but it also stores water like a sponge. Soil pH was lower than the optimum and thus will negatively affect plant growth and influence other soil variables (Marx et al., 1999).

Tree canopies intercept rainfall that reduces rainfall intensity, especially the canopy of mature trees in old growth stands (as in our study area), which causes raindrops to accumulate into larger droplets and eventual release as throughfall. Hence, the kinetic energy of the raindrops increases (Stuart and Edwards, 2006; Gerrits et al., 2010; Geißler et al., 2013; Holz et al., 2015).

The present study showed that the straw and the sawdust mulches after logging operations on the skid trails reduced both runoff and sediment. Indeed, mulch application on the bare, disturbed and compacted soil created coverage that increased water absorption, reduced the raindrop and throughfall energy and the rainfall kinetic energy, increased infiltration, and decreased splash erosion. The results were consistent with other research and revealed that the wood material mulch and straw significantly reduced soil erosion (Stuart and Edwards, 2006; Wade et al., 2012; Wear et al., 2013; Wagenbrenner et al., 2015; Cristan et al., 2016; Robichaud et al., 2016). After skidding operations, the intact litter layer is completely destroyed, then raindrops directly hit the exposed mineral soil layer, and due to the low infiltration rate of soil, the soil becomes water-saturated, resulting in surface runoff, sediment, erosion, and accelerated leaching of mineral nutrients from the skid trails (Kozlowski, 1999; Stuart and Edwards, 2006). In contrast, Sawyers et al. (2012) and Wade et al. (2012) found that straw mulch were more effective than slash in decreasing sediment yield.

The runoff reduction of 35.03 and 72.6%, respectively, from the straw- and the sawdust-mulched plots is similar to the more than 50% reduction in runoff reported by Fernández and Vega (2016b), Sawyers et al. (2012) (reducing erosion by 3.29 Mg ha\(^{-1}\) yr\(^{-1}\)), Wade et al. (2012) (reducing erosion by 3 t ha\(^{-1}\) yr\(^{-1}\)) and Wear et al. (2013) studies; however, the type of mulch and application rate of the mulch in these studies differed from those used here. In the present study, the straw and the sawdust mulches reduced sediment yield relative to the control plots by 57.5% and 88.3%, respectively, consistently with the results of other research (Sawyers et al., 2012; Wade et al., 2012; Wear et al., 2013; Robichaud et al., 2016). Also, the cover provided by the mulches in those experiments and ours differed. Wagenbrenner et al. (2015) found that scattering logging slash on ski trails provide 50% coverage reduced sediment production by 2–20% of the values from the untreated skidder trail plots, similar to our findings. Similarly, Fernández and Vega (2016b) found that mulching with eucalypt bark strands at a rate of 11 Mg ha\(^{-1}\) significantly reduced soil losses after logging by 2.3 Mg ha\(^{-1}\).

On the other hand, soil disturbance, litter layer loss and soil compaction negatively affect water infiltration into the soil layer of ski trails. Accordingly, surface runoff and sediment yield were higher in the control plots. Wagenbrenner et al. (2015) found that the less-trafficked feller-buncher trails also had significantly higher sediment production rates than the controls did. Notably, the sawdust and the straw mulches allowed more rain to fall before runoff and loss of sediment began, and also controlled and decreased the severity of runoff and sediment as rainfall increased. A very important feature of sawdust mulch after rainfall is its adhesiveness; it forms a hard layer that does not allow water to infiltrate the substrate layer, and it also caused to absorb water, and finally acted as a water absorbent layer (microdam).

However, Fernández and Vega (2014) reported that bark strands and straw mulches reduced soil erosion after fire, and that mulches with eucalypt bark strands seemed less useful for protecting soil than straw mulch because the bark decomposed very quickly. Thus, the results of the present research indicated that the flow of water was not powerful enough to remove soil particles because the depth of the straw and sawdust mulch trapped any loosened soil aggregates (Sadeghi et al., 2015).

In the present study, the highest runoff and sediment level in the control plot occurred during the leafless period. Soil cover removal often increases soil erosion by 10–100 times, while tree canopy removal without disturbing the soil cover increases soil erosion rate by 10–20% only (Hartanto et al., 2003; Stuart and Edwards, 2006). Hoseini et al. (2011) found that the average rainfall interception in a beech forest was 24.24% from May to late October in the Kheyrud Forest. Also in the different climate condition, Gerrits et al. (2010) found that in a beech forest (Huewelerbach), the canopy intercepted on average 7% in winter and 15% in summer. The interception is highly seasonal, and storage capacity of the tree canopy also has a seasonal pattern. The potential evaporation changes throughout the year and is higher in summer, so the storage capacity alters in deciduous tree stands (Herbst et al., 2008; Gerrits et al., 2010; Hoseini et al., 2011). Herbst et al. (2008) found that during the year about 29% of the gross rainfall was intercepted in the leafed period and 20% in the leafless period in a mixed deciduous forest.

Result show that the sawdust mulch was most effective in decreasing runoff and sediment yield, followed by the straw mulch treatment. This wood-based material (sawdust mulch) lacks the negative aspects of rice straw mulch; it is resistant to wind and is at low risk for transfer of seeds from non-native and invasive plants. In other studies, agricultural straw was susceptible to wind, especially on slopes, which moved the straw to other areas (Bhattacharyya et al., 2010; Robichaud et al., 2013; Prat et al., 2014; Vega et al., 2014; Sadeghi et al., 2015; Fernández and Vega, 2016a); some areas then lacked mulch, and other parts had thicker layers (Robichaud et al., 2013). Further, applying the rice and the wheat straw mulch may bring invasive and non-native plant species or quarantined pests into the forest (Robichaud et al., 2013).

In the study area, all the dominant tree species seasonally lose their leaves (commonly during autumn). Also, leaf-out of tree species begins the growing season in the temperate Hyrcanian forests and is one of the most important factors affecting hydrological processes. In the deciduous or summer-green forest (e.g., the Hyrcanian forests), the forest canopy cover intercepts rainfall, but that benefit is lost after the leaves drop; both situations greatly impact the water balance of the forest floor. Concurrence of the leafless period with losses from the forest floor loss intensifies surface runoff and sediment yield (Hartanto et al., 2003; Stuart and Edwards, 2006; Dung et al., 2012; Webb et al., 2012; Ida et al., 2013).

The lack of differences in the amount of runoff and sediment among spring, autumn and winter can be related to several factors. First, we can conclude from the results in Fig. 7, that increasing runoff and sediment is associated with increasing rainfall in the study area. Second, the leafless period in the study area started on October 30, 2015 and lasted until April 16, 2016, which includes part of the fall season, all of the winter season, and part of the spring season. As a result, in these three seasons in the control plots, not only did the forest lack canopy cover, but the forest floor cover was also lost due to skidding operations. Therefore, each rainfall event led to runoff and sediment yield and was the main reason that the amount of runoff and sediment did not differ significantly among the fall, winter and spring.

However, the straw and sawdust mulch helped decrease the amount of runoff and sediment compared with that in the control plots. On the other hand, despite significant rainfall in the summer (198 mm), the amount of sediment and runoff in this study differed significantly from that in the other seasons and was lowest as a result of the canopy cover, drier weather, higher temperature and evapotranspiration.

Positive linear responses (Fig. 7), between runoff and sediment to increasing rainfall and regression coefficients represent the mean change in the response variable for one unit of change in the predictor.
variable while holding other predictors in the model constant. This statistical control provided by regression analysis is important because it isolates the role of one variable from all of the others in the model.

The correlation between rainfall and runoff show that in the same rainfall intensities, runoff (or sediment) variations were linear and depending on the type of treatment, there was a different upward trend; in any rainfall intensity, the amount of runoff (or sediment) in straw mulch was greater than that of sawdust. Also, the slope of regression line in the straw treatment was more than sawdust (Fig. 7).

Although the study lasted over 1 year, the decomposition rate of these mulches also needs to be considered because the decay rate will affect the duration and efficacy of the soil cover. Rice straw mulch is produced in rice agricultural lands downstream along the Caspian Sea, and sawdust mulch is produced from wood processing and wood industries, but from an economic viewpoint, cost estimations regarding these two types of mulch should also be considered at the application area (Schuler and Briggs, 2000; Wear et al., 2013).

Deposition and compaction of litter or slash to increase surface roughness can decrease overland flow and rill initiation on the skid trails (Litschert and MacDonald, 2009). However, on the steeper skid runon roughness can decrease overland these two types of mulch should also be considered at the application area (Schuler and Briggs, 2000; Wear et al., 2013).

It is noteworthy that harvesting in the study area occurred through the straw treatment was more than sawdust (Fig. 7). In any rainfall intensity, the amount of runon depending on the type of treatment, there was a different period, provided canopy and ground covers and surface roughness.

Predicting the impact of logging operations in the watershed scale, however, is very difficult, because the impact depends not only on the amount of surface covered by skid trails, but also on the extent that skid trails directly deliver runoff and sediment to streams (Smith et al., 2011; Wagenbrenner et al., 2015).

5. Conclusions

We examined the effectiveness of sawdust and straw mulching on postharvest runoff and sediment yield on the skid trails in the deciduous forest, northern Iran, at a plot scale from natural rainfall. The results revealed that the straw and sawdust plots decreased runoff by 75.0% and 72.6% and sediment yield by 57.5% and 88.3%, respectively. A linear relationship between rainfall and runoff, and sediment yields was determined in this study. According to our findings, in the deciduous Hyrcanian forest, the leafless period and the subsequent increase in surface runoff are important factors, in addition to the decrease in runoff contributed by the canopy cover during the leafed period. Thus, covering the bare, compacted soil on the skid trail and depots can significantly reduce surface runoff and sediment yield. As a consequence, we recommend that skidding operations be designed and limited to pre-planned skid trails because machine traffic off the skid trail can significantly disturb the soil and increase soil bulk density. Our results indicated that applications of straw and sawdust mulch immediately following the skidding operations reduces surface runoff and sediment on the skid trails. The findings also suggest that mulching after skidding is most useful for reducing soil losses and enabling vegetation regrowth before the start of the leafless period in the Hyrcanian forest.

Acknowledgements

The authors are very thankful to Dr. Hazen for her helpful English editing and comments. We thank two anonymous reviewers for helpful comments to improve the manuscript.

References

143–150.


