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# Response of Runoff and Sediment on Skid Trails of Varying Gradient and Traffic Intensity over a Two-Year Period

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**Abstract:** Compacted soil has lower water infiltration and hydraulic conductivity, which contributes to increased runoff and erosion on slopes. The aim of the present study was to assess runoff and sediment on three skidding trail longitudinal gradients (15%, 25%, and 35%) and different levels of machine traffic (low, medium, and high), over a two-year period following the impact in the Hyrcanian forest, Iran. The results show that trail gradient and traffic intensity have a significant effect on soil bulk density and total porosity on the skid trails. The average runoff amount varied significantly among trail gradients and ranged from 1.59 mm on the 15% trail gradient and 2.76 mm on the 25% trail gradient, to 4.76 mm on the 35% trail gradient in the low traffic intensity. Average sediment also increased significantly with increasing trail gradient. Average sediment was 0.01 kg $m^{-2}$, 0.03 kg $m^{-2}$, and 0.05 kg $m^{-2}$ on the low traffic intensity in the first year for the 15%, 25%, and 35% trail gradients, respectively. The largest runoff and sediment occurred in the first year and stressed the need for applying forestry Best Management Practices such as the use of brush mats during harvesting operations, as well as the installation of water diversion structures or seeding immediately after initial soil compaction and disturbance, in order to protect the bare soil from heavy rainfall.

**Keywords:** forest harvesting; forest soils; soil quality; recovery; machines

## 1. Introduction

One of the most important practices in managed forest stands is forest harvesting and wood extraction. Logging operations, especially ground-based skidding using heavy rubber-tired machinery, have been on the rise in mechanized harvesting. The use of machines operated directly in forest stands can have drastic effects on forest soils, such as compaction and rutting. This is particularly the case since forest soils have a high organic matter content, low bulk density, and high porosity, which increases their vulnerability to compaction and other forms of disturbances. When high wheel loads resulting from the weight of the skidding machine and its load are exerted on the soil surface layer of skid trails, soil particles are pushed closer together and the bulk density increases, while soil porosity, aeration, and infiltration capacity decrease substantially [1–4].

Soil compaction and disturbance are also strongly affected by several factors, such as initial bulk density, particle size distribution, soil organic matter [2], moisture content, trail gradient [3,5,6], machine weight, and traffic intensity (number of machine passing over a respective area [7,8]). The impacts of heavy machine loads exerted on forest soils can negatively affect soil health and modify soil mechanical properties. For instance, compacted soil often exhibits lower water infiltration and hydraulic conductivity, which contributes to increased runoff and erosion on slopes [9–12].

Logging operations can influence runoff generation and sediment yield through change in the forest stand at two levels. In the first level, forest harvesting, through the removal of trees, alters the forest canopy cover, which reduces canopy interception, decreases the evapotranspiration rate, and increases throughfall volume to the intact litter layer [13–17]. However, these changes occurring at the surface soil eventually lead to alterations in the litter layer, whereby the litter decomposition rate increases due to change in light and moisture conditions under the forest canopy. In the second level, the removal of a previously intact litter layer due to soil disturbance and compaction can reduce the infiltration rate and increase surface runoff and sediment production [18–24]. The reduction or removal of organic materials in the form of peat can also decrease wash erosion and lessen the splash detachment by raindrops [25]. A number of studies have recognized significant increases in runoff and sediment following logging operations [11,26]. It is well documented that a reduction in vegetation cover following forest harvesting also increases the runoff volume and sediments [15,20,23,24,27].

Trail gradient is a main factor that has a significant effect on soil particle detachment and transport, as well as runoff erodibility [28–32]. Several studies have focused on the effect of trail gradient, length, and shape on runoff generation and soil loss [32–35]. Şensoy and Kara [35] found that runoff and soil loss were greater in uniform plots (ground without slope failure) than in concave and convex plots on a 30% trail gradient. The variability between uniform and concave gradients may explain the differences in the energy of runoff available for erosion. Liu et al. [32] reported that the runoff rate decreased as the terrain gradient increased, while sediment losses increased as terrain gradient increased. Defersha et al. [36] found that as the gradient increased from 9% to 25%, the splash erosion and sediment yield increased.

Other studies have assessed the effects of post-fire salvage logging on runoff and sediment losses at the plot scale [16,17,27,37–39]. Malvar et al. [16] found that runoff generation was equal for the control and the intermediate soil disturbance class following post-fire salvage logging. In addition, sediment rates increased with increasing soil disturbance, and were 1.6 and three times greater in the intermediate and most disturbed areas than in the control.

In the Hyrcanian forests (northern Iran), the highest runoff and sediment were observed in skid trails and in the area without canopy cover (1.13 mm and 0.62 mm, and 1.2 g $m^{-2}$, and 0.51 g $m^{-2}$). In contrast, the forest with selective harvesting treatments and the natural forest without harvesting exhibited the lowest amounts of average runoff (0.44 mm and 0.2 mm) and sediment (0.17 $m^{-2}$ and 0.1 g $m^{-2}$ [11]). In this forest, the runoff and sediment relative to untreated skid trail plots (8 $m^2$) in a severely compacted loam soil were 1.62 mm and 0.079 kg $m^{-2}$, respectively, during the first year after harvesting [12]. The recovery of soil physical properties after logging operations has been well documented. Physical properties of a severely compacted soil do not naturally recover over a short time frame [1,10,40,41]. In the Hyrcanian forest, rut depth and soil moisture content were recovered on skid trails, but 20 years was not a sufficient period of time for the bulk density and total porosity, particularly on steep slopes, to recover to pre-impact conditions [3]. In northeastern France, soil porosity recovery was not sufficient at least three to four years post impact [42]. In Germany, no recovery of soil aeration was observed at a depth of 12–24 cm during the three-year monitoring period following mechanized harvesting [43]. In Lower Saxony, Germany, the bulk density on three different soil types was not fully recovered (Cambisols on lime stone, Cambisols at loess-covered sandstone, Podzols on glacial drift and sands) over a 40-year period [4]. All these studies support the fact that soil natural rehabilitation following machine induced impacts can be a lengthy process.

A few studies have been conducted on the long-term impact of forest harvesting on runoff and sediment, and hydrologic recovery. Hydrologic recovery refers to the decreasing impact of forest practices through time as a result of vegetation regrowth [20]. Croke et al. [26] found that runoff and sediment production decreased markedly within the five-year monitoring period.

One of the most important issues in the skid trails following mechanized operations is how the runoff and sediment changes in the trails over time as a function of varying trail gradient and traffic intensity. However, those variables have not yet been tested over a multi-year period, particularly in a deciduous forest. Therefore, the aim of the present study was to assess the runoff and sediment of three longitudinal trail gradients (15%, 25%, and 35%) exposed to different levels of ground-based machine traffic (low, medium, and high), over a two-year period following mechanized harvesting.

## 2. Materials and Methods

### 2.1. Site Description

The research was performed in compartment No. 315 of the Gorazbon District in the Kheyrud Forest (40°46′ N and between 55°49′ E and 55°58′ E) in the Hyrcanian forest of northern Iran between 23 May 2015 and 10 February 2017 (Figure 1). The terrain ranges in altitude from 1150 m to 1250 m above sea level and lies on a southern aspect. The region had a 30-year mean annual temperature of 12.8 °C with the lowest temperatures in February and a mean annual precipitation of 1260 mm, with a maximum mean monthly rainfall of 253 mm in October and a minimum rainfall of 41 mm in July. Soils are classified as Alfisols [44] with a soil texture ranging from silt loam to loamy. The study area is dominated by natural forests with native mixed deciduous tree species, including beech (*Fagus orientalis* Lipsky) and hornbeam (*Carpinus betulus* L.). In these forest types, the dominant silvicultural treatment is a combination of group selection and single-tree selection (close to nature silviculture). During the operation in May 2015, trees were felled motor-manually with a chain saw and then skidded to the landing area in proximity to a forest road using a 4WD Timberjack 450C rubber-tired skidder.

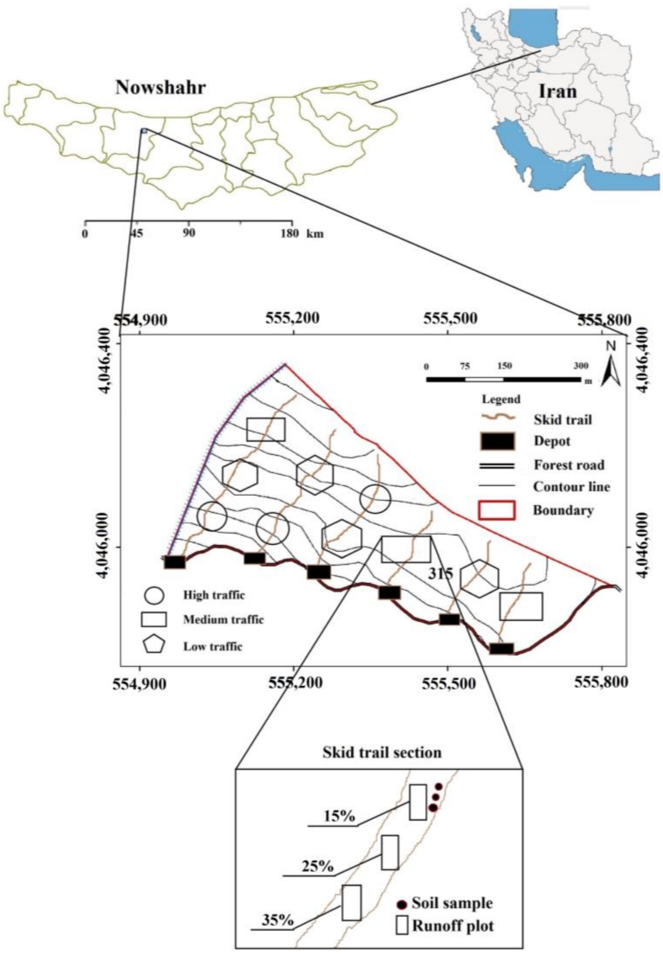


**Figure 1.** Layout of the study area and experimental design in the Hyrcanian forest.

### 2.2. Experimental Design

This study measured the potential recovery of runoff and sediment occurring within various sampling plots over a two-year horizon. Sampling plots were established in different skid trail segments on three trail gradients (15%, 25%, and 35%) exposed to different levels of machine traffic (low; 3–4, medium; 9–10, and high; >15 machine cycles), which were monitored by field observation. A machine cycle consisted of one empty pass and one loaded pass performed on the selected skid trail segment. Therefore, treatments included 54 combinations of three levels of trail gradient, three levels of traffic intensity, and two periods of assessment (referred to as years), replicated in three plots. All the combinations were tested on a total of six skid trails. As shown in Figure 1, three runoff plots were established on gradients of 15%, 25%, and 35% on a skid trail with a specified traffic volume. At the time of skidding, weather conditions had been very dry and warm and these conditions remained constant during the wood extraction operation that lasted two months.

To avoid disturbance, the following variables were measured within a skid trail in an area adjacent to each runoff plot: Soil bulk density, porosity, organic matter, litter depth, canopy cover, and soil particle size distribution. More specifically, three soil samples were collected near each runoff plot and the forest canopy cover was estimated in three locations near each plot. Soil sample cores were taken from the top mineral soil (from soil surface down to a depth of 10 cm) using a thin-walled steel cylinder that was 40 mm long and 56 mm in diameter, driven horizontally into the soil by a hammer-driven device [45]. After extracting the steel cylinder, soil cores were trimmed flush with the cylinder ends and extruded into a plastic bag for transport to the laboratory. Samples were weighed on the day they were collected and again after oven drying at 105 °C until a constant mass was reached to determine the water content and bulk density. Soil organic matter was determined using the Walkley-Black method [46], whereas particle size distribution was determined using the hydrometer method [47].

### 2.3. Rainfall, Runoff, and Sediment Measurements

Immediately after skidding operations, three 10 $m^2$ plots (5 m $\times$ 2 m) were established for each trail gradient class and traffic intensity on the skid trail (total of 27 plots including replicates) to measure surface water runoff and sediment. The perimeter of each plot was defined by inserting pieces of a wooden board into the soil to a depth of 20 cm and extended above the soil surface by approximately 15 cm to prevent input from the adjacent area. A plastic pipe of a 3 cm diameter was used to convey the runoff water to a 100 L reservoir located at the bottom side of the slope. Due to budgetary restrictions and the low forest road density in the area (long skidding distances), the monitoring of natural rainfall events was chosen as opposed to artificial and more controlled irrigation methods as used in Lane et al. [48]. After each rainfall, the runoff volume was measured using a graduated cylinder, and runoff samples were filtered, oven-dried at 105 °C, and weighed to determine the suspended sediment yield. The reservoirs were cleaned after each rainfall event. In addition, runoff material was transferred to the lab for further processing and the reservoirs were emptied and cleaned. Data were collected from a total of ten rainfall events for each year (totaling 20 rainfall events for the two-year study period). During 2015–2016, the mean rainfall intensity for the experiments was 26.7 $\pm$ 23.0 mm $day^{-1}$ and ranged from 9.8 mm $day^{-1}$ to 79 mm $day^{-1}$. Within the second year (2016–2017), mean rainfall intensity ranged between 8.8 mm $day^{-1}$ and 73.4 mm $day^{-1}$ (31.7 $\pm$ 19.9 mm $day^{-1}$, on average). Within a one-year period, deciduous trees within the study area exhibited one leafless and one leafed period. To quantify runoff and sediment during peak conditions, our study focused on the leafless period.

### 2.4. Statistical Analyses

The experimental design was a completely randomized design whereby plots were randomly assigned to the trail gradient, traffic intensity, and year. Generalized linear modeling (GLM, two-way analysis of variance) was applied to relate runoff and sediment responses to trail gradient, traffic intensity, and year. Since no departure of the data from a normal distribution was determined by the Kolmogorov-Smirnov test ($\alpha$ = 0.05), standard parametric analyses were carried out. Homogeneity of variance among treatments was verified by Levene's test ($\alpha$ = 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 done 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 trail gradient and traffic intensity treatments, and both years in the leafless period. The SPSS (release 17.0; SPSS, Chicago, IL, USA) statistical package was used for analyses.

## 3. Results

### 3.1. Soil Properties

Selected properties presented in Table 1 show differences in bulk density, total porosity, organic matter, litter depth, canopy cover, and soil particle distribution among trail gradient and traffic intensity classes on the skid trail. Trail gradient and traffic intensity have a significant effect on soil bulk density and total porosity on the skid trails (Table 1). The amount of sand, clay, and silt particles did not differ significantly ($p \leq 0.05$) among the treatments, nor did canopy cover. The amount of organic matter significantly decreased as traffic intensity increased at each gradient class; however, a significant difference between organic matter in the low and medium traffic intensity at each trail gradient was not detected. A minimal thickness of litter remained following the low traffic intensity class, but was non-existent after high traffic.

**Table 1.** Selected soil physical properties before the experiment started in 2015 in the runoff sample plots.

| Trail Gradient (%) | Traffic Intensity | Number of Samples | Bulk Density (g cm$^{-3}$) | Porosity (%) | Organic Matter (%) | Litter Depth (cm) | Canopy Cover (%) | Sand (%) | Silt (%) | Clay (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| 15 | low | 9 | 1.11 ± 0.03 $^{c}$ | 57.3 ± 0.8 $^{a}$ | 4.8 ± 0.9 $^{a}$ | 1.6 ± 0.6 $^{a}$ | 43 ± 6 $^{a}$ | 30 | 44 | 26 |
| | medium | 9 | 1.16 ± 0.05 $^{b}$ | 55.4 ± 1.2 $^{b}$ | 4.3 ± 0.8 $^{a}$ | 0.4 ± 0.2 $^{b}$ | 46 ± 5 $^{a}$ | 33 | 31 | 36 |
| | high | 9 | 1.23 ± 0.09 $^{a}$ | 52.7 ± 2.3 $^{b}$ | 2.2 ± 0.3 $^{b}$ | 0 | 47 ± 6 $^{a}$ | 37 | 32 | 31 |
| 25 | low | 9 | 1.13 ± 0.06 $^{c}$ | 56.5 ± 1.5 $^{a}$ | 2.7 ± 0.4 $^{a}$ | 0.1 ± 0.04 $^{a}$ | 42 ± 9 $^{b}$ | 29 | 43 | 28 |
| | medium | 9 | 1.28 ± 0.05 $^{b}$ | 50.8 ± 1.6 $^{b}$ | 1.7 ± 0.3 $^{b}$ | 0 | 45 ± 5 $^{a}$ | 35 | 29 | 36 |
| | high | 9 | 1.32 ± 0.08 $^{a}$ | 49.2 ± 2.4 $^{b}$ | 1.4 ± 0.2 $^{b}$ | 0 | 38 ± 7 $^{b}$ | 28 | 34 | 38 |
| 35 | low | 9 | 1.21 ± 0.07 $^{c}$ | 53.5 ± 2.1 $^{a}$ | 0.8 ± 0.1 $^{a}$ | 0.05 ± 0.01 $^{a}$ | 46 ± 4 $^{a}$ | 27 | 41 | 32 |
| | medium | 9 | 1.39 ± 0.04 $^{b}$ | 46.5 ± 1.3 $^{b}$ | 0.5 ± 0.2 $^{b}$ | 0 | 44 ± 8 $^{a}$ | 34 | 39 | 27 |
| | high | 9 | 1.47 ± 0.08 $^{a}$ | 43.5 ± 2.7 $^{c}$ | 0.3 ± 0.1 $^{b}$ | 0 | 49 ± 5 $^{a}$ | 34 | 38 | 28 |

Note: Different letters after means within each treatment indicate significant differences by Duncan's test ($p < 0.05$).

### 3.2. Runoff

Trail gradient, traffic intensity, and year (all $p \leq 0.001$), as well as the interaction effects of trail gradient × traffic intensity, and trail gradient × year (all $p \leq 0.012$), significantly affected runoff, but not the interaction of trail gradient × traffic intensity × year ($p = 0.615$; Table 2). Following skidding operations in the low traffic intensity, average runoff varied significantly amongst trail gradient classes with values of 1.59 mm, 2.76 mm, and 4.76 mm for the 15%, 25%, and 35% trail gradients, respectively. Hence, average runoff increased significantly with increasing trail gradient (Table 3).

**Table 2.** ANOVA for the effect of trail gradient, traffic intensity, and year, and their interaction on runoff and sediment.

| Source | d.f. | *F* | | *p* Value | |
|---|---|---|---|---|---|
| | | Runoff (mm) | Sediment (kg m$^{-2}$) | Runoff | Sediment |
| Year | 1 | 81.17 | 381.07 | ≤0.001 ** | ≤0.001 ** |
| Trail gradient | 2 | 71.77 | 182.29 | ≤0.001 ** | ≤0.001 ** |
| Traffic intensity | 2 | 76.11 | 228.79 | ≤0.001 ** | ≤0.001 ** |
| Year × Trail gradient | 2 | 4.43 | 48.22 | 0.012 ** | ≤0.001 ** |
| Year × Traffic intensity | 2 | 6.07 | 65.18 | 0.002 ** | ≤0.001 ** |
| Trail gradient × Traffic intensity | 4 | 10.92 | 29.98 | ≤0.001 ** | ≤0.001 ** |
| Year × Trail gradient × Traffic intensity | 4 | 0.67 | 6.57 | 0.615 $^{ns}$ | ≤0.001 ** |

Note: * $p < 0.05$; ** $p < 0.01$; ns: Not significant; d.f.: degree of freedom.

**Table 3.** Means (±std) of runoff (mm) on different trail gradients, traffic intensities, and years.

| Trail Gradient (%) | Average Runoff (mm) | | | | | |
|---|---|---|---|---|---|---|
| | Year One | | | Year Two | | |
| | Traffic Intensity | | | Traffic Intensity | | |
| | Low | Medium | High | Low | Medium | High |
| 15 | 1.59 ± 0.15 $^{bC}$ | 2.81 ± 0.16 $^{bB}$ | 5.06 ± 0.11 $^{bA}$ | 0.31 ± 0.02 $^{cC}$ | 0.53 ± 0.04 $^{cB}$ | 1.17 ± 0.09 $^{cA}$ |
| 25 | 2.76 ± 0.74 $^{bB}$ | 10.69 ± 0.36 $^{aA}$ | 15.34 ± 0.32 $^{aA}$ | 0.77 ± 0.03 $^{bC}$ | 3.67 ± 0.07 $^{bB}$ | 6.48 ± 0.04 $^{bA}$ |
| 35 | 4.76 ± 0.29 $^{aB}$ | 13.05 ± 0.19 $^{aA}$ | 18.31 ± 0.65 $^{aA}$ | 1.28 ± 0.02 $^{aC}$ | 7.25 ± 0.09 $^{aB}$ | 11.38 ± 0.04 $^{aA}$ |

Note: Different letters after means within each treatment indicate significant differences by Duncan's test ($p < 0.05$). Capital case letters refer to the comparisons among the three traffic intensity groups at different trail gradients for each year (row). Lower case letters refer to the comparison among the three trail gradient classes in each traffic intensity group and year (column); std: standard deviation.

During the first year after skidding, average runoff on all trail gradients increased with increasing traffic intensity. The most significant runoffs were observed at trail gradients of 35% and 25% for high traffic intensity (18.31 mm and 15.34 mm) and at trail gradients of 35% and 25% for medium traffic intensity (13.05 mm and 10.69 mm). However, amounts of runoff did not differ significantly between high and medium traffic intensities at trail gradients of 35% and 25%. By increasing the traffic intensity from low to high classes, the runoff amount increased 2.2 times on 15%, 4.6 times on 25%, and 2.8 times on 35% trail gradient (Table 3).

Following the two-year test period, average runoff at the three trail gradients also increased significantly with increasing traffic intensity. However, the major increases following skidding occurred on the steepest trail gradient, particularly on the medium and high traffic intensity classes. Regardless of traffic intensity, average runoff two years after trafficking continued to be higher with increasing trail gradient. The highest average runoff values were observed on the 35% trail gradient subjected to high traffic intensity (Table 1), which also experienced the greatest amount of relative change.

Two years after timber extraction, average runoff continued to vary significantly among traffic intensity classes. Compared to the first year, the runoff amount decreased by 73.1 % at low, 44.4% at medium, and 37.8% at high traffic intensity classes on the 35% trail gradient. After two years from timber extraction, average runoff from all three trail gradients was 0.79 mm at low, 3.8 mm at medium, and 6.3 mm at high traffic intensity classes, thus equaling a decrease of 74% at low, 57% at medium, and 51% at high traffic intensity classes (Table 3). Two year after the skidding operation, averaged in all three traffic intensities, runoff was 0.67 mm at 15%, 3.6 mm at 25%, and 6.6 mm at 35% trail gradient classes. In other words, after two years following skidding operations, runoff decreased by 78% at the 15% trail gradient, 62% at the 25% gradient, and 44% at the 35% gradient (Table 3).

### *3.3. Sediment Yield*

Sediment losses were significantly affected by trail gradient, traffic intensity, and year (all $p \leq 0.001$), as well as the interaction effects of trail gradient × traffic intensity, trail gradient × year (all $p \leq 0.001$), and trail gradient × traffic intensity × year ($p \leq 0.001$; Table 2). In both years and for all trail gradients, the average sediment increased significantly with increasing traffic intensity classes and reached the highest level of 0.31 kg $m^{-2}$ following one year after skidding operations (Table 4). Average sediment within the first year following low traffic intensity increased significantly with increasing trail gradient classes and was 0.01 kg $m^{-2}$ on the 15%, 0.03 kg $m^{-2}$ on the 25%, and 0.05 kg $m^{-2}$ on the 35% trail gradient.

**Table 4.** Means (±std) of sediment (kg $m^{-2}$) on different trail gradients, traffic intensities, and years.

| Trail Gradient (%) | Average Sediment (kg $m^{-2}$) | | | | | |
|---|---|---|---|---|---|---|
| | Year One | | | Year Two | | |
| | Traffic Intensity | | | Traffic Intensity | | |
| | Low | Medium | High | Low | Medium | High |
| 15 | 0.010 ± 0.008 $^{cC}$ | 0.024 ± 0.007 $^{cB}$ | 0.079 ± 0.008 $^{cA}$ | 0.007 ± 0.005 $^{bB}$ | 0.010 ± 0.006 $^{bAB}$ | 0.013 ± 0.008 $^{bA}$ |
| 25 | 0.030 ± 0.003 $^{bC}$ | 0.170 ± 0.006 $^{bB}$ | 0.240 ± 0.016 $^{bA}$ | 0.011 ± 0.008 $^{bC}$ | 0.037 ± 0.003 $^{bB}$ | 0.080 ± 0.027 $^{bA}$ |
| 35 | 0.050 ± 0.003 $^{aC}$ | 0.220 ± 0.019 $^{aB}$ | 0.310 ± 0.014 $^{aA}$ | 0.016 ± 0.001 $^{aC}$ | 0.056 ± 0.002 $^{aB}$ | 0.110 ± 0.031 $^{aA}$ |

Note: Different letters after means within each treatment indicate significant differences by Duncan's test ($p < 0.05$). Capital case letters refer to the comparisons among the three traffic intensity groups at different trail gradients for each year (row). Lower case letters refer to the comparison among the three trail gradient classes in each traffic intensity group and year (column).

In the first year, the amounts of soil loss were significantly greater at a gradient of 35% compared to 25% for the medium and high traffic intensity classes, as well as between low, medium, and high traffic intensities on all trail gradients in the second year after skidding operations. In the first year, the lowest amounts of sediment loss were observed at a gradient of 15% on all traffic intensity classes (0.01–0.079 kg $m^{-2}$). In both the first and second year, the amounts of sediment were also lowest at the low traffic intensity and differed significantly between low, medium, and high traffic intensity in all trail gradient classes.

When averaged for the first year and all three trail gradients, sediments were 0.300 kg $m^{-2}$ at low, 0.140 kg $m^{-2}$ at medium, and 0.210 kg $m^{-2}$ at high traffic intensity classes. Averaged over both years and all three trail gradients, sediments were 0.021 kg $m^{-2}$ at low, 0.086 kg $m^{-2}$ at medium, and 0.139 kg $m^{-2}$ at high traffic intensity classes. After a two-year period from skidding operations, sediment decreased by 62% at low, 75% at medium, and 68% at high traffic intensity classes for all three trail gradients (Table 4). When averaged for the first year and all three traffic intensities, sediments were also 0.038 kg $m^{-2}$, 0.147 kg $m^{-2}$, and 0.193 kg $m^{-2}$ for 15%, 25%, and 35% trail gradient classes, respectively. Averaged over both years and all three traffic intensities, sediments were 0.024 kg $m^{-2}$ at a 15% gradient, 0.095 kg $m^{-2}$ at a 25% gradient, and 0.127 kg $m^{-2}$ at a 35% gradient. Therefore, two years after skidding operations, sediments decreased in all three traffic intensities tested by 73%, 71%, and 68% for 15%, 25%, and 35% trail gradient classes, respectively (Table 4).

Sediment rates were higher with increasing runoff intensity while tending to increase as the trail gradient and traffic intensity increased (Figure 2). A regression analysis between runoff and sediment revealed a significant change in the linear sediment response to runoff for the low, medium, and high traffic intensities for the gradients 35%, 25%, and 15% for both the first and second year. In any specific amount of runoff, the sediment yield from the high traffic plot was higher than from the medium traffic, and the sediment level from the medium traffic treatment was higher than from the low traffic treatment. In the second year, not only did the sediment level decrease as runoff dropped sharply, but the sediment yield was also lower than in the first year (Figure 2).

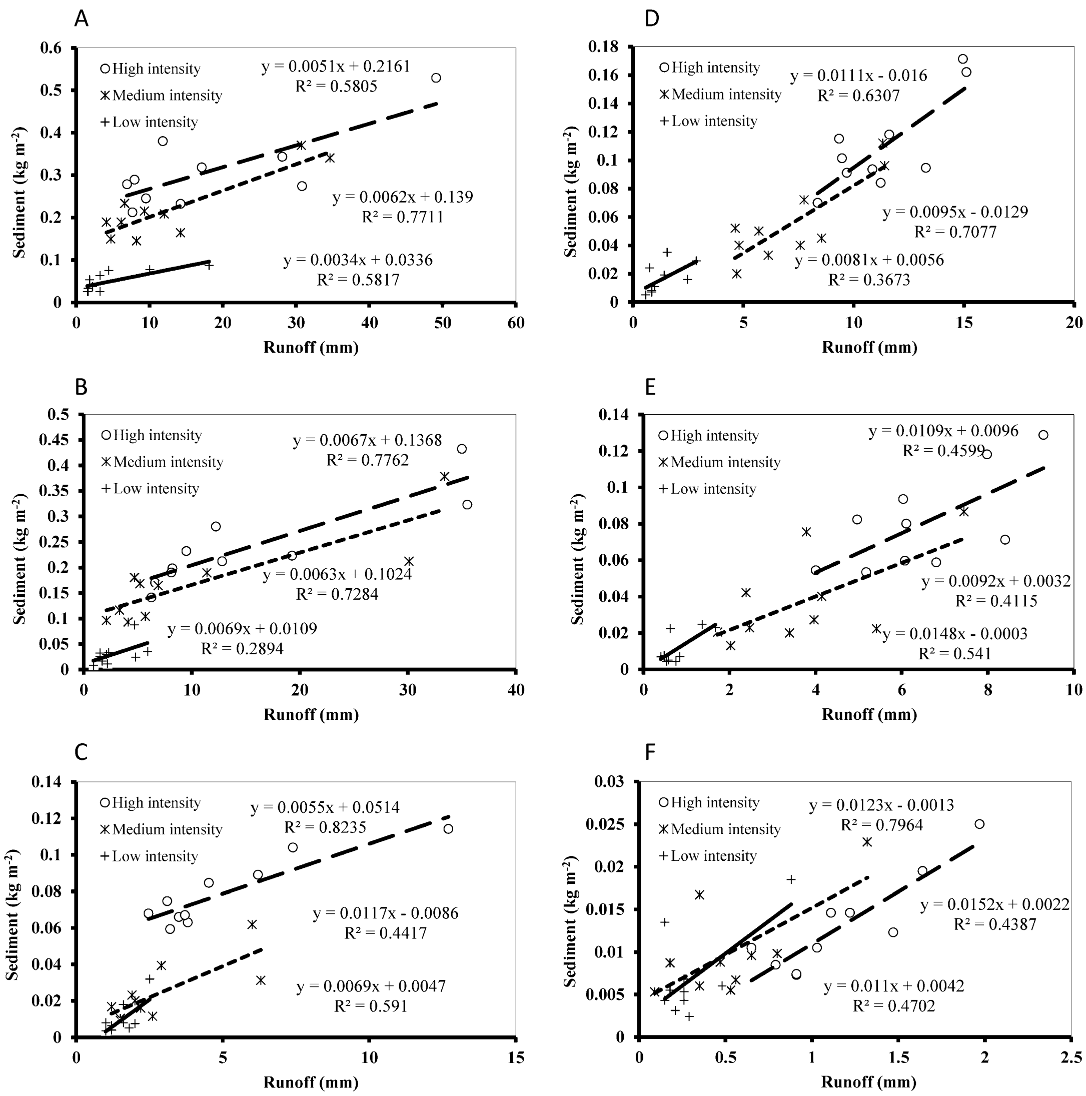


**Figure 2.** The relationship between runoff and sediment in the treatments during first year (**A**–**C**) and second year (**D**–**F**), and trail gradient 35% (**A**,**D**), 25% (**B**,**E**), and 15% (**C**,**F**). For each graph, the regression equation between responses and treatment, and the coefficient of determination ($R^2$) are given. High, medium, and low traffic intensities are identified by long dashes, short dashes, and solid lines, respectively.

## 4. Discussion

### *4.1. Soil Properties*

The results show that bulk density significantly increased with traffic intensity. These findings are consistent with the result of many studies mentioning that soil compaction occurs as traffic intensity increases [1–4,8]. Soil bulk densities also increased statistically as the trail gradient increased. The majority of studies have documented that the trail gradient effects the extent and degree of soil compaction and disturbance [5,6]. Generally, displacement of the organic layer and mineral soil occurs by scalping, log rolling, gouging, rutting, and puddling [1–3]. In addition, Ekwue and Harrilal [25] reported that soil compaction causes an increase in surface runoff and soil loss, and decreases infiltration. Afterwards, the litter layer and the organic matter content decreased with machine traffic increasing. The intact litter layer can protect soil from rainfall splashing and the throughfall kinetic energy, and can serve as a water absorbent layer. Peat (or organic matter content) reduces soil strength and its inter-aggregate stability [25].

### 4.2. Runoff

The high clay content (>26%, Table 1) in our study likely decreased the soil strength and increased the cohesiveness of soil particles, thus leading to high plastic deformability and finally small pore sizes. As a result, these physical changes could decrease infiltration rates and lead to higher surface runoff. The results also demonstrated that minimum soil disturbance happened in the skid trails with the low traffic intensity, where the surface litter layer and organic matter content showed the lowest changes compared to other traffic intensities. Litter depth and soil organic matter typically play an important role in absorbing rainfall and rain-drop velocity, thus reducing runoff and soil loss on the skid trail over the recovery period. Similar results have been reported in laboratory experiments by Ekwue and Harrilal [25], where litter depth and soil organic matter were found to act as mulch, thereby protecting the soil surface from the direct impact of raindrops.

After skidding operations, the intact litter layer was completely disturbed and mixed with top soil. Under such conditions during a rain event, raindrops would directly hit the exposed mineral soil layer and, due to the low infiltration rate of the soil, soil saturation of the upper soil horizon would occur and contribute to the surface runoff, sediment, erosion, and accelerated leaching of mineral nutrients from the skid trails [9,13]. The results show that trail gradient and traffic intensity significantly affect runoff and sediment yield. Findings from a majority of studies were consistent with our result, mentioning that the loss of vegetation cover by forest harvesting increased the surface runoff volume and the sediment yield [13,14,18–24]. It is well documented that skid trails are a major source of runoff generation and sediments [13,17,18,24,27].

In a deciduous forest, leaves dropped from trees provide a steady source of organic material to the soil, which in turn decays and becomes humus each year. Ekwue and Harrilal [25] found that peats and organic materials reduced soil loss by decreasing the bulk density, increasing infiltration, and reducing runoff. In the second year, the runoff and sediment yield significantly decreased. One explanation for this event is that soil particles on the skid trail detached due to rain-drops during the first year and created a sealed soil surface. While runoff was produced in the second year, sediment significantly decreased compared to first year. The presence of cracks or macropores in the upper soil horizons, combined with leaves dropped after the first year, changed the soil infiltration capacity. In line with the current study, Croke et al. [26] reported that surface infiltration rates on the skid trails increased and erosion rates declined over the five-year period. Moreover, the single-tree selection treatments increased the growth of residual trees which resulted in canopy closure after two years from harvesting in the study area. Dung et al. [14] reported that significant recovery in canopy closure occurred from the first to the second year of the post-thinning period. In our study, the runoff decreased by 50–60% after two years, while sediment yield decreased by 70% during this time. The runoff decrease in the first year was nearly twice the amount observed in the second year, which shows that the soil physical properties did not recover over time. However, dropped leaves and organic material after trafficking contributed to providing a coating layer on the skid trail, which caused a sediment decline over the assessment period. This is in line with findings from Croke et al. [26], who reported that the largest percentage of soil loss occurs within 1 $\pm$ 2 years after disturbance and that rates decrease exponentially with time.

### 4.3. Sediment Yield

The development of rill networks and reduction of surface roughness also play an important role in runoff reinfiltration processes, by limiting the residence time of flow on the slope [34]. Jourgholami and Etehadi Abari [12] reported that the average runoff and sediment yield on the 8-$m^2$ plots (4 m $\times$ 2 m) located on a skid trail were 1.62 mm and 0.079 kg $m^{-2}$, respectively. Etehadi Abari et al. [11] mentioned that the highest runoff and sediment were observed on skid trails (1.13 mm and 1.2 g $m^{-2}$, respectively) on 2-$m^2$ (2 m $\times$ 1 m) plots, while the natural forest without harvesting and the forest with selective harvesting treatments exhibited the lowest amounts of average runoff (0.2 mm and 0.44 mm) and sediment (0.1 g $m^{-2}$ and 0.17 g $m^{-2}$). In the current research, the plot size was 10-$m^2$, hence, the runoff and sediment yield were higher than those measured in the previous studies conducted by Etehadi Abari et al. [11] and Jourgholami and Etehadi Abari [12]. Similarly, Kinnell [49] mentioned that slope length and gradient influence the type of erosion that occurs in a plot.

The results of the current research show that by increasing the trail gradients in the treatments, the average runoff also increases. Trail gradient affected the velocity of runoff water which resulted in a greater erosive power of the water [28,29]. Torri and Poesen [50] found that the soil surface slope has a positive effect on splash detachment. The results of studies conducted by Fu et al. [30], Moreno de las Heras et al. [34], and Şensoy and Kara [35] also indicate that the amounts of runoff and soil loss increased with increasing trail gradient. Numerous studies have indicated that the degree of soil erosion is related to rainfall intensity and trail gradient [31,32]. Moreover, Fang et al. [31] found that an increase in trail gradient enhanced the water flow velocity and reduced the chance that runoff would infiltrate into the soil. Similarly, Ekwue and Harrilal [25] indicated that the mean cumulative infiltration decreased from 6.6 mm to 4.3 mm; mean cumulative runoff increased from 17.9 mm to 39.0 mm; and soil erosion increased from 1.56 kg to 2.78 kg in each case when the soil gradient increased from 9% to 30%. On the contrary, Liu et al. [32] found that runoff rates declined as the trail gradient increased.

Overall, sediment production was significantly related to rainfall intensity and reduced by vegetation regrowth compared to low intensity plots. By increasing the traffic intensity, the amount of sediment increased. Interestingly, the rainfall splash detachment supplied enough loose soil particles for runoff transport. The extent of degradation of the vegetation strongly influences the capacity of slope systems to slow, retain, and store overland flow [34]. Rainfall intensity also dramatically affected the amount of runoff and erosion. For all three gradient classes, a close relationship was observed between sediment yield and runoff for all the traffic intensities during the two-year monitoring period. Zhang and Wang [51] reported that rainfall intensity affected not only the detachment of soil materials, but also enhanced sediment transport.

The largest runoff and sediment occurred in the first year, stressing the need to apply the forestry BMPs such as mulching, water diversion structures, and seeding, immediately after initial soil compaction and disturbance to protect bare soil from heavy rainfall.

## 5. Conclusions

In this study, the runoff and sediment have been assessed for three trail longitudinal gradients (15%, 25%, and 35%), each exposed to different levels of machine traffic (low, medium, and high machine traffic) over a two-year recovery period after trafficking at a plot scale under natural rainfall conditions. Trail gradient and traffic intensity on a skid trail had a significant effect on soil bulk density and total porosity. The average runoff increased significantly with increasing trail gradient. Over two years, trails with a gradient over 25% that were exposed to high traffic intensity had the highest amount of runoff. Sediment production increased with increasing traffic intensity and trail gradient classes. This increase could be explained by the higher soil compaction and reduced soil shear strength of disturbed plots. The runoff in the first year compared to the second year shows that the soil physical properties did not recover over time. After a two-year period from skidding operations, runoff and sediment decreased significantly at all traffic intensity classes and for all three trail gradients. However, dropped leaves and organic material provided the organic layer on the skid trail and bare soil, which caused a decline in sediment over the recovery period. Both runoff and sediment yield tended to decrease with time since the initial soil compaction, highlighting the importance of BMP implementation. Some BMPs that can be applied in order to reduce runoff and sediment in similar conditions are:

- Skidding operations should be restricted to trail segments with a longitudinal gradient of less than 25%; these should occur when the soil is drier or, if possible, with deep snow cover.

- Brush from harvesting debris should be applied to the skid trail surface to provide a protection layer over the bare soil to reduce runoff and sediment.
- Water diversion structures (waterbars) should be inserted in the skid trail system to disperse the runoff from trails to intact forest floor.

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## References

1. Rab, M.A. Recovery of soil physical properties from compaction and soil profile disturbance caused by logging of native forest in Victorian central highlands, Australia. *For. Ecol. Manag.* **2004**, *191*, 329–340. [CrossRef]
2. Ampoorter, E.; Schrijver, A.; Nevel, L.; Hermy, M.; Verheyen, K. Impact of mechanized harvesting on compaction of sandy and clayey forest soils: Results of a meta-analysis. *Ann. For. Sci.* **2012**, *69*, 533–542. [CrossRef]
3. Ezzati, S.; Najafi, A.; Rab, M.A.; Zenner, E.K. Recovery of soil bulk density, porosity and rutting from ground skidding over a 20-year period after timber harvesting in Iran. *Silva Fenn.* **2012**, *46*, 521–538. [CrossRef]
4. Ebeling, C.; Lang, F.; Gaertig, T. Structural recovery in three selected forest soils after compaction by forest machines in Lower Saxony, Germany. *For. Ecol. Manag.* **2016**, *359*, 74–82. [CrossRef]
5. Gayoso, J.; Iroume, A. Compaction and soil disturbances from logging in Southern Chile. *Ann. Sci. For.* **1991**, *48*, 63–71. [CrossRef]
6. Jourgholami, M.; Soltanpour, S.; Etehadi Abari, M.; Zenner, E.K. Influence of slope on physical soil disturbance due to farm tractor forwarding in a Hyrcanian forest of northern Iran. *iForest-Biogeosci. For.* **2014**, *7*, 342–348. [CrossRef]
7. Labelle, E.R.; Jaeger, D. Soil compaction caused by cut-to-length forest operations and possible short-term natural rehabilitation of soil density. *Soil Sci. Soc. Am. J.* **2011**, *75*, 2314–2329. [CrossRef]
8. Majnounian, B.; Jourgholami, M. Effects of rubber-tired cable skidder on soil compaction in Hyrcanian forest. *Croat. J. For. Eng.* **2013**, *34*, 123–135.
9. Kozlowski, T.T. Soil compaction and growth of woody plants. *Scand. J. For. Res.* **1999**, *14*, 596–619. [CrossRef]
10. Cambi, M.; Certini, G.; Neri, F.; Marchi, E. The impact of heavy traffic on forest soils: A review. *For. Ecol. Manag.* **2015**, *338*, 124–138. [CrossRef]
11. Etehadi Abari, M.; Majnounian, B.; Malekian, A.; Jourgholami, M. Effects of forest harvesting on runoff and sediment characteristics in the Hyrcanian forests, northern Iran. *Eur. J. For. Res.* **2017**, *136*, 375–386. [CrossRef]
12. Jourgholami, M.; Etehadi Abari, M. Effectiveness of sawdust and straw mulching on postharvest runoff and soil erosion of a skid trail in a mixed forest. *Ecol. Eng.* **2017**, *109*, 1–9. [CrossRef]
13. Stuart, G.W.; Edwards, P.J. Concepts about forests and water. *North. J. Appl. For.* **2006**, *23*, 11–19.
14. Dung, B.X.; Gomi, T.; Miyata, S.; Sidle, R.C.; Kosugi, K.; Onda, Y. Runoff responses to forest thinning at plot and catchment scales in a headwater catchment draining Japanese cypress forest. *J. Hydrol.* **2012**, *444–445*, 51–62. [CrossRef]
15. Cristan, R.; Aust, W.M.; Bolding, M.C.; Barrett, S.M.; Munsell, J.F.; Schilling, E. Effectiveness of forestry best management practices in the United States: Literature review. *For. Ecol. Manag.* **2016**, *360*, 133–151. [CrossRef]
16. Malvar, M.C.; Silva, F.C.; Prats, S.A.; Vieira, D.C.S.; Coelho, C.O.A.; Keizer, J.J. Short-term effects of post-fire salvage logging on runoff and soil erosion. *For. Ecol. Manag.* **2017**, *400*, 555–567. [CrossRef]

17. Wagenbrenner, J.W.; MacDonald, L.H.; Coats, R.N.; Robichaud, P.R.; Brown, R.E. Effects of post-fire salvage logging and a skid trail treatment on ground cover, soils, and sediment production in the interior western United States. *For. Ecol. Manag.* **2015**, *335*, 176–193. [CrossRef]
18. Hartanto, H.; Prabhu, R.; Widayat, S.E.; Asdak, C. Factors affecting runoff and soil erosion: Plot-level soil loss monitoring for assessing sustainability of forest management. *For. Ecol. Manag.* **2003**, *180*, 361–374. [CrossRef]
19. Brown, A.E.; Zhang, L.; McMahon, T.A.; Western, A.W.; Vertessy, R.A. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *J. Hydrol.* **2005**, *310*, 28–61. [CrossRef]
20. Moore, R.D.; Wondzell, S.M. Physical Hydrology and the Effects of Forest Harvesting in the Pacific Northwest: A Review. *J. Am. Water Res. Assoc.* **2005**, *41*, 763–784. [CrossRef]
21. Wade, C.R.; Bolding, M.C.; Aust, W.M.; Lakel, W.A. Comparison of five erosion control techniques for bladed skid trails in Virginia. *South. J. Appl. For.* **2012**, *36*, 191–197. [CrossRef]
22. Webb, A.A.; Dragovich, D.; Jamshidi, R. Temporary increases in suspended sediment yields following selective eucalypt forest harvesting. *For. Ecol. Manag.* **2012**, *283*, 96–105. [CrossRef]
23. Ide, J.; Finér, L.; Laurén, A.; Piirainen, S.; Launiainen, S. Effects of clear-cutting on annual and seasonal runoff from a boreal forest catchment in eastern Finland. *For. Ecol. Manag.* **2013**, *304*, 482–491. [CrossRef]
24. Holz, D.J.; Williard, K.W.J.; Edwards, P.J.; Schoonover, J.E. Soil Erosion in Humid Regions: A review. *J. Contemp. Water Res. Educ.* **2015**, *154*, 48–59. [CrossRef]
25. Ekwue, E.I.; Harrilal, A. Effect of soil type, peat, slope, compaction effort and their interactions on infiltration, runoff and raindrop erosion of some Trinidadian soils. *Biosyst. Eng.* **2010**, *105*, 112–118. [CrossRef]
26. Croke, J.; Hairsine, P.; Fogarty, P. Soil recovery from track construction and harvesting changes in surface infiltration, erosion and delivery rates with time. *For. Ecol. Manag.* **2001**, *143*, 3–12. [CrossRef]
27. Smith, H.G.; Sheridan, G.J.; Lane, P.N.J.; Bren, L.J. Wildfire and salvage harvesting effects on runoff generation and sediment exports from radiata pine and eucalypt forest catchments, south-eastern Australia. *For. Ecol. Manag.* **2011**, *261*, 570–581. [CrossRef]
28. Koulouri, M.; Giourga, C. Land abandonment and slope gradient as key factors of soil erosion in Mediterranean terraced lands. *Catena* **2007**, *69*, 274–281. [CrossRef]
29. Ekwue, E.I.; Bharat, C.; Samaroo, K. Effect of soil type, peat and farmyard manure addition, slope and their interactions on wash erosion by overland flow of some Trinidadian soils. *Biosyst. Eng.* **2009**, *102*, 236–243. [CrossRef]
30. Fu, S.; Liu, B.; Liu, H.; Xu, L. The effect of slope on interrill erosion at short slopes. *Catena* **2011**, *84*, 29–34. [CrossRef]
31. Fang, H.; Sun, L.; Tang, Z. Effects of rainfall and slope on runoff, soil erosion and rill development: An experimental study using two loess soils. *Hydrol. Process.* **2015**, *29*, 2649–2658. [CrossRef]
32. Liu, D.; She, D.; Yu, S.; Shao, G.; Chen, D. Rainfall intensity and slope gradient effects on sediment losses and splash from a saline–sodic soil under coastal reclamation. *Catena* **2015**, *128*, 54–62. [CrossRef]
33. Bracken, L.J.; Kirkby, M.J. Differences in hillslope runoff and sediment transport rates within two semi-arid catchments in southeast Spain. *Geomorphology* **2005**, *68*, 183–200. [CrossRef]
34. Moreno de las Heras, M.; Nicolau, J.M.; Merino-Martin, L.; Wilcox, B.P. Plot-scale effects on runoff and erosion along a slope degradation gradient. *Water Resour. Res.* **2010**, *46*, 4503. [CrossRef]
35. Sensoy, H.; Kara, O. Slope shape effect on runoff and soil erosion under natural rainfall conditions. *iForest-Biogeosci. For.* **2014**, *7*, 110–114. [CrossRef]
36. Defersha, M.B.; Quraishi, S.; Melesse, A. The effect of slope steepness and antecedent moisture content on interrill erosion, runoff and sediment size distribution in the highlands of Ethiopia. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 2367–2375. [CrossRef]
37. Wagenbrenner, J.W.; Robichaud, P.R.; Brown, R.E. Rill erosion in burned and salvage logged western montane forests: Effects of logging equipment type, traffic level, and slash treatment. *J. Hydrol.* **2016**, *541*, 889–901. [CrossRef]
38. Fernández, C.; Vega, J.A. Effects of mulching and post-fire salvage logging on soil erosion and vegetative regrowth in NW Spain. *For. Ecol. Manag.* **2016**, *375*, 46–54. [CrossRef]

39. Prats, S.A.; Wagenbrenner, J.; Malvar, M.C.; Martins, M.A.S.; Keizer, J.J. Mid-term and scaling effects of forest residue mulching on post-fire runoff and soil erosion. *Sci. Total Environ.* **2016**, *573*, 1242–1254. [CrossRef] [PubMed]
40. Williamson, J.R.; Neilsen, W.A. The effect of soil compaction, profile disturbance and fertilizer application on the growth of eucalypt seedlings in two glasshouse studies. *Soil Tillage Res.* **2003**, *71*, 95–107. [CrossRef]
41. Zenner, E.K.; Fauskee, J.T.; Berger, A.L.; Puettmann, K.J. Impacts of skidding traffic intensity on soil disturbance, soil recovery, and aspen regeneration in north central Minnesota. *North. J. Appl. For.* **2007**, *24*, 177–183.
42. Goutal, N.; Renault, P.; Ranger, J. Forwarder traffic impacted over at least four years soil air composition of two forest soils in northeast France. *Geoderma* **2013**, *193–194*, 29–40. [CrossRef]
43. Fründ, H.-C.; Averdiek, A. Soil aeration and soil water tension in skidding trails during three years after trafficking. *For. Ecol. Manag.* **2016**, *380*, 224–231.
44. United States Department of Agriculture (USDA). *Soil Taxonomy: Keys to Soil Taxonomy*, 8th ed.; United States Department of Agriculture, Natural Resources Conservation Service: Washington, DC, USA, 1998.
45. Blake, G.R.; Hartge, K.H. Bulk density. In *Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods*; Klute, A., Ed.; American Society of Agronomy and Soil Science: Madison, WI, USA, 1986; pp. 363–375.
46. Walkley, A.; Black, I.A. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of chromic acid titration method. *Soil Sci.* **1934**, *37*, 29–38. [CrossRef]
47. Gee, G.W.; Bauder, J.W. Particle-size analysis. In *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods*; Klute, A., Ed.; Soil Science Society of America: Madison, WI, USA, 1986; pp. 383–411.
48. Lane, P.N.L.; Croke, J.C.; Dignan, P. Runoff generation from logged and burnt convergent hillslopes: Rainfall simulation and modelling. *Hydrol. Process.* **2004**, *18*, 879–892. [CrossRef]
49. Kinnell, P.I.A. A review of the design and operation of runoff and soil loss plots. *Catena* **2016**, *145*, 257–265. [CrossRef]
50. Torri, D.; Poesen, J. The effect of soil surface slope on raindrop detachment. *Catena* **1992**, *19*, 561–578. [CrossRef]
51. Zhang, X.C.; Wang, Z.L. Interrill soil erosion processes on steep slopes. *J. Hydrol.* **2017**, *548*, 652–664. [CrossRef]