

Article

The Effects of Organic Mulches on Water Erosion Control for Skid Trails in the Hyrcanian Mixed Forests

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Abstract: Ground-based skidding can lead to severe soil disturbance by increasing surface water flow and soil erosion. Organic mulches have been shown to be effective in contrasting this type of soil disturbance, although the cost/benefit aspect has yet to be studied. This study, by installing runoff sample plots, aims to elucidate the effects of litter (LM) and sawdust (SM) mulches with three application rates (litter: 7.6 Mg ha⁻¹ LM7.6, 14.6 Mg ha⁻¹ LM14.6, 22.5 Mg ha⁻¹ LM22.5; sawdust: 5.3 Mg ha⁻¹ SM5.3, 11.4 Mg ha⁻¹ SM11.4, 16.7 Mg ha⁻¹ SM16.7) on runoff, soil, and nutrient loss (nitrate and phosphate) in skid trails established in the Hyrcanian forest. The results were also compared to the undisturbed area (UND) and to an untreated skid trail (UNT). The results showed that both litter and sawdust mulch significantly decreased runoff, soil loss, and nitrate and phosphate loss. The values of runoff, runoff coefficient, soil loss, NO₃, and PO₄ were at the highest level in the untreated skid trails (UNT). The runoff, runoff coefficient, soil loss, NO₃, and PO₄ gradually decreased as the application rate of both the litter (LM) and sawdust (SM) mulches increased. According to the results, it is possible to conclude that the mulch application rates of 7.6–14.6 Mg ha⁻¹ and 5.3–11.4 Mg ha⁻¹ for litter and sawdust mulch, respectively, can be applied to maintain soil and water conservation after logging operations on skid trails. The obtained findings can help to shape specific best-management practices for the implementation of sustainable forest operations in the context of the study area, by indicating suitable mulch types and application rates to decrease the negative effects of erosion.

Keywords: logging operation; litter; sawdust; runoff; soil loss; nitrate; phosphate; nutrient loss



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1. Introduction

Forest soils play a key role in maintaining the fertility, health, and services of the ecosystem [1–3] and provide nutrients, organic matter, and water [4–6]. Maintaining proper soil quality is one of the key goals of sustainable forest management, taking into consideration that enhanced erosion is among the major concerns of ground-based forest operations [7–9]. This aspect is of pivotal importance when considering the effects of climate change, which is expected to increase the number of extreme rainfall events [10–12].

The increasing need for wood for multiple purposes [13–15] has been fostering the implementation of mechanized forest harvesting with heavy machinery to maximize the cost-effectiveness of forest operations [16–18]. Increasing machine weight also means increased environmental disturbances of machinery traffic on the forest soil and its subsequent impact on forest stand fertility [19–21]. The primary effect of ground-based forest operations on

soil is compaction, which can dramatically decrease the balance and regulation of forest fertility by destroying the soil structure and disrupting the soil's physical properties [22–25]. Among the main consequences of soil compaction (an increase in the bulk density of soil after the passage of a machine), there are a decrease in porosity in the soil volume [26–28], a decrease in the connection of pore spaces [29–31], an increase in the soil volume density and strength [32–34], and reduced water infiltration and gas exchange [35–37]. Furthermore, soil compaction can lead to substantial disturbances to several aspects of the forest soil ecosystem, such as fine roots and microarthropod biodiversity [38–40].

Among the various parameters of the soil of temperate deciduous forests that can be affected by ground-based forest operations, erosion has shown the fastest recovery time [41–43]. Numerous studies have confirmed that soil erosion in skid trails was at its highest rate in the first years after machine traffic events and then decreased significantly, primarily due to vegetation regrowth [8,44,45]. For example, Boggs et al. [46] studied the effect of forest harvesting on water quantity and quality in North Carolina, USA, and showed that the amount of sediment as well as the amount of nitrate in the water reached its maximum value two years after harvesting, and then its value decreased, probably as a consequence of the regrowth of tree and understory vegetation. Also, in Canada, Glaz et al. [47] investigated the effect of forest harvesting on the water quality of lakes near harvested forests, and showed a significant difference in the amount of phosphorus in the control and logged samples one year after disturbance. However, this effect seems to decrease after two years, indicating that the system is highly resilient and may be able to return to its initial conditions in terms of the assessed water quality parameters. Therefore, the most important implication to deal with in terms of the negative effects of soil erosion on topsoil after logging operations is the rapid restoration of the soil surface through vegetation [48,49]. Traditional methods of soil and water conservation include engineering, biological, and agronomic approaches. Although the benefits of soil and water conservation from engineering and biological measures have been widely reported, these methods are still difficult to implement in developing countries due to economic constraints. As an important low-cost remedial measure, mulch has therefore received worldwide attention due to its affordable cost and rapid effect. However, the cost effectiveness of these restoration programs and techniques has yet to be clearly estimated.

Mulch is any organic or inorganic material (such as litter, straw, leaves, plastic film, gravel, etc.) that is scattered on the soil surface to protect the soil [50,51]. The application of mulch can absorb raindrop impacts, increase surface roughness, improve the soil bulk density and the porosity and stability of the aggregates, and increase the penetration rate, water storage capacity, and organic matter content [52,53]. Runoff, as well as the amount of sediment and nutrients in the runoff, is reduced by mulch, and this is achieved by increasing the surface roughness and reducing the ground flow rate and runoff velocity [54,55].

Previous studies have clearly confirmed the effectiveness of organic mulch in reducing soil and water loss in different climatic environments around the world, with reductions of up to 65% in comparison to soil without mulching [56,57]. However, the effectiveness of mulching treatments depends on various factors such as the soil conditions, rainfall erosion, the length and degree of slope, and the type and rate of mulching application [58]. Despite the fact that the beneficial effects of mulching are known, more studies are needed to observe water, soil, and nutrient conservation processes, especially in areas where soil erosion is a significant threat [59]. This research represents the first proper attempt to evaluate the effectiveness of mulching, not only regarding erosion, but also nutrient loss in the study area. Research on the optimal rate of mulch application when the cost is a limiting factor is also needed to extend the knowledge of mulch efficiency and to better protect water and soil in forested areas. This study therefore aims to fulfill the specific knowledge gap concerning the effectiveness of sawdust and litter as mulch materials, not only to prevent erosion but also nutrient loss, in the context of the study area, where the extensive forest harvesting with heavy machinery that has been implemented in recent decades could be particularly detrimental for soil conservation.

Organic mulches derive from a wide range of materials such as straw, crop residues, forest residues, wood chips, pine bark, branches, leaves, litter, dry grass, and hydro-mulch [4]. The two most frequently used mulch materials in the Hyrcanian forests are litter and sawdust. Litter mulch generally includes the undecomposed leaves of hornbeam (*Carpinus betulus* L.) trees, which are collected from the litter layer in the area. Sawdust mulch is obtained from the harvesting operations in the study area, mostly from felling and processing with a chainsaw.

The Hyrcanian mixed broadleaf forest ecosystem is located at the southern edge of the Caspian Lake and the northern edge of Alborz, with an area of 55,000 square kilometers. These forests are considered among the most valuable forests in the world and are known as a natural museum. The climate in the Hyrcanian forests is dry during the summer, and humid during spring and autumn; the winters are often mild.

This case study was developed to test the following research hypotheses:

- (1) Both litter and sawdust are suitable mulching materials for reducing runoff and nutrient loss in the skid trails;
- (2) Sawdust is more effective than litter as a mulch material;
- (3) For both litter and sawdust mulch, a higher application rate implies higher efficiency in reducing runoff and nutrient loss.

The results of this study can help aid in our understanding of the effectiveness of the investigated mulching types within the scope of reducing erosion and nutrient loss, and also to identify the optimal application rates. In this way, it is possible to define clear best-management practices to be implemented in the context of the study area, thus limiting the environmental concerns of forest harvesting and ensuring soil conservation.

2. Materials and Methods

2.1. Site Description

This study was conducted in cutting block no. 114 in the Patom district in Kheyroud forest research station of the University of Tehran, North of Iran (51°33'33" E and 51°34'43" E and 36°35'14" N and 36°34'53" N) (Figure 1). This cutting block is highly representative of the forest stands of the study area. The area is 38.4 ha, with an altitude ranging between 650 and 770 m above sea level. The main aspect is in the north–west direction, with a prevalent slope of 20–30%. The soil of the study area is weakly acidic brown forest soil with limestone bedrock (classified as Luvisols according to the World Reference Base for Soil Resources—IUSS-WRB, 2022). According to the weather station data, the study area is highly humid, with cold winters, an annual rainfall of 1300 mm, and an average annual temperature of 12.2 °C (recorded over 30 years (1985–2015) by the Nowshahr synoptic weather station located in the airport, at a distance of 15 km from the study area). The forest stand is an uneven-aged high forest with three strata of *Fagus orientalis* Lipsky (*Oriental beech*), with *Carpinus betulus* L. (hornbeam) and *Acer velutinum* Boiss. (velvet maple), and a combination of 60% Oriental beech, 10% hornbeam, 15% velvet maple, and 15% of other species, including *Acer cappadocicum* Gled. (*Cappadocian maple*), *Tilia platyphyllos* Scop. (large-leaved lime tree), and *Diospyros lotus* L. (date-plum).

Wood harvesting has been suspended since 2006 in the Patom district due to livestock grazing, and only the conservation plan was applied. In the past, the silviculture method was the single selection method, and windthrow trees were harvested in 2015–2016. Timber extraction from the stump area to the landing was performed during the spring season. Skidding operations were performed with a TAF E655 wheeled cable skidder, as is common in the study area, equipped with a double-drum winch in March, April, and May 2016. Some important characteristics of this skidder are its 48 kW engine power, unloaded weight of 6.8 Mg, tire inflation pressure of 220 kPa, and average skidding load of 2.86 m³ per skidding cycle, creating skid trails with a longitudinal gradient ranging between 10 and 23% and an average width of 3.6 m.

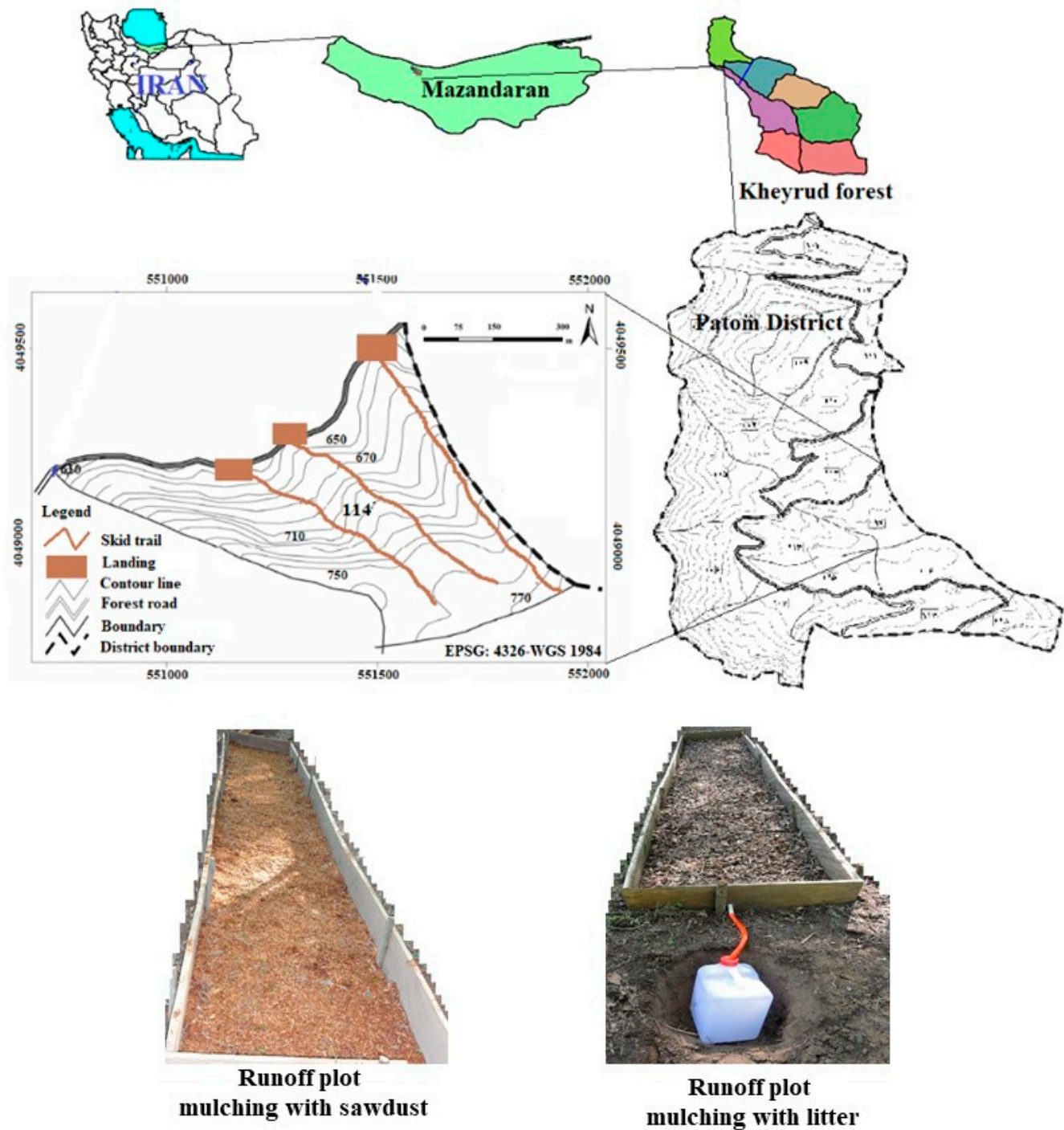


Figure 1. The study area in the Kheyrud forest in the Hyrcanian forests and runoff plots mulched with sawdust and litter.

2.2. Experimental Design

After the completion of wood extraction operations with a TAF wheeled skidder through March, April, and May 2016, a runoff plot was installed to measure the runoff, sediments, and nitrate and phosphate loss in the skid trails. Wooden boards were dipped 20 cm into the soil to prevent the surface seepage of the samples and obtain an accurate runoff measurement. Specifications such as the skid trail slope and the number of vehicle passes were considered constant at the time of the plot installations. The studied treatments included litter mulch with three application rates (7.6, 14.6, and 22.5 Mg ha⁻¹) as LM7.6,

LM14.6, and LM22.5; sawdust mulch (5.3, 11.4, and 16.7 Mg ha⁻¹) as SM5.3, SM11.4, and SM16.7; untreated skid trails (UNTs); and undisturbed areas (UNDs). Three runoff plots measuring 1 × 6 m, along with a storage tank at the bottom of each runoff plot, were installed in each treatment. At the end of the study period, the runoff was measured, and samples were taken to the laboratory for evaluations of the sediment, nitrate, and phosphatase loss. A manual rainfall gauge was installed for measuring the amount of rain beside the plots and in open areas [41]. In order to investigate the correlation between the obtained hydrological data and other physical variables of the soil, three samples at a distance of 1 m and a random starting point were taken from the vicinity of each runoff plot. The following characteristics were measured: the soil bulk density, porosity, organic matter, sand, silt, and clay. Moreover, the litter depth was measured at the sample location, and the canopy percentage was estimated based on ocular observation.

2.3. Data Collection and Laboratory Analysis

After each rainfall event, the gathered rainfall in each rain gauge was accurately measured using graduated cylinders (Equation (1)) [41]:

$$D_{Pg} = \frac{V_{Pg}}{A_c} \quad (1)$$

D_{Pg} is the rainfall mount, V_{Pg} is the total rainfall volume gathered with the rain gauge, and A_c is the area of the rain gauge opening. The runoff was also gathered and measured after each rainfall event.

The minimum interval between two rain events is considered to be at least 6 h. The runoff coefficient was calculated by dividing the runoff amount by the rainfall amount in each event. For measuring the sediment, 1 L of each runoff sample was poured into the beaker. After the sediments settled, the water on top was drained and the sediments were transferred to containers that had been weighed. Afterwards, they were kept in an oven for 24 h at a temperature of 105 °C, and the weight of the sediments per liter were measured. The concentration of all sediments in each rain event was determined. A spectrophotometer device was used for the measurement of the phosphatase and nitrate contents. The soil bulk density was measured by using a defined-volume cylinder. The wet and dry weights of the soil were calculated by dividing the dry weight of the soil by the cylinder volume and soil moisture content [60]. The soil moisture content was measured by drying soil samples at 105 °C for 24 h [61]. The soil samples were ground with a pestle into a powder and then passed through a 2 mm sieve. The soil particle size distribution was measured using the hydrometer method [62]. The soil particle density was measured using the ASTM D854-00 2000 standard [61]. The porosity percentage of the soil was calculated by dividing the soil bulk density by the soil particle density. The soil organic C was measured using the Walkley–Black technique [63].

2.4. Statistical Analyses

After data gathering and measurement, the information was entered into the Microsoft Excel 2019 software (Microsoft, Redmond, USA). In order to verify the normality of the data and the homogeneity of the variances, Kolmogorov–Smirnov and Levene tests were employed, respectively. As the data were normal, one-way analysis of variance tests were conducted to elucidate the effect of the treatments on the runoff, runoff coefficient, sediment, nitrate, and phosphate. A post hoc Duncan test was applied to examine the differences among the treatments. Moreover, the Spearman correlation test was used to assess the relationship between the treatments, runoff, runoff coefficient, sediment, nitrate, phosphate, and the soil physical properties ($p \leq 0.05$). The SPSS software (version 20; SPSS, Chicago, IL, USA) was used for the statistical analysis, while the figures and plots were generated using the Excel software.

3. Results

3.1. Runoff and Sediment Yield

The comparison of the rainfall and runoff graphs at the different levels of litter mulch showed that LM7.6 had the highest runoff volumes of 9.03 and 9.21 mm in two rainfall events, with volumes of 50.1 and 65.8 mm, respectively. The second-level litter mulch (LM14.6) had the highest runoff values of 5.7 and 5.29 mm in two corresponding rainfall events of 50.1 and 42.7 mm, respectively.

A comparison of the rainfall and runoff graphs at the different levels of sawdust mulch showed that, at the three rainfall events of 50.9, 65.8, and 37.3 mm, SM5.3 had the highest runoff volumes of 6.47 and 84.4 mm, respectively. SM11.4 had the highest runoff values of 4.05 and 3.91 mm in the two corresponding rainfalls of 50.1 and 65.8 mm, respectively. SM16.7 also had the highest runoffs of 3.08 and 3.63 mm in two rainfall events of 50.1 and 50.9 mm, respectively (Figure 2). A similar trend was revealed concerning the relation between rainfall and sediment in the runoff water (Figure 3).

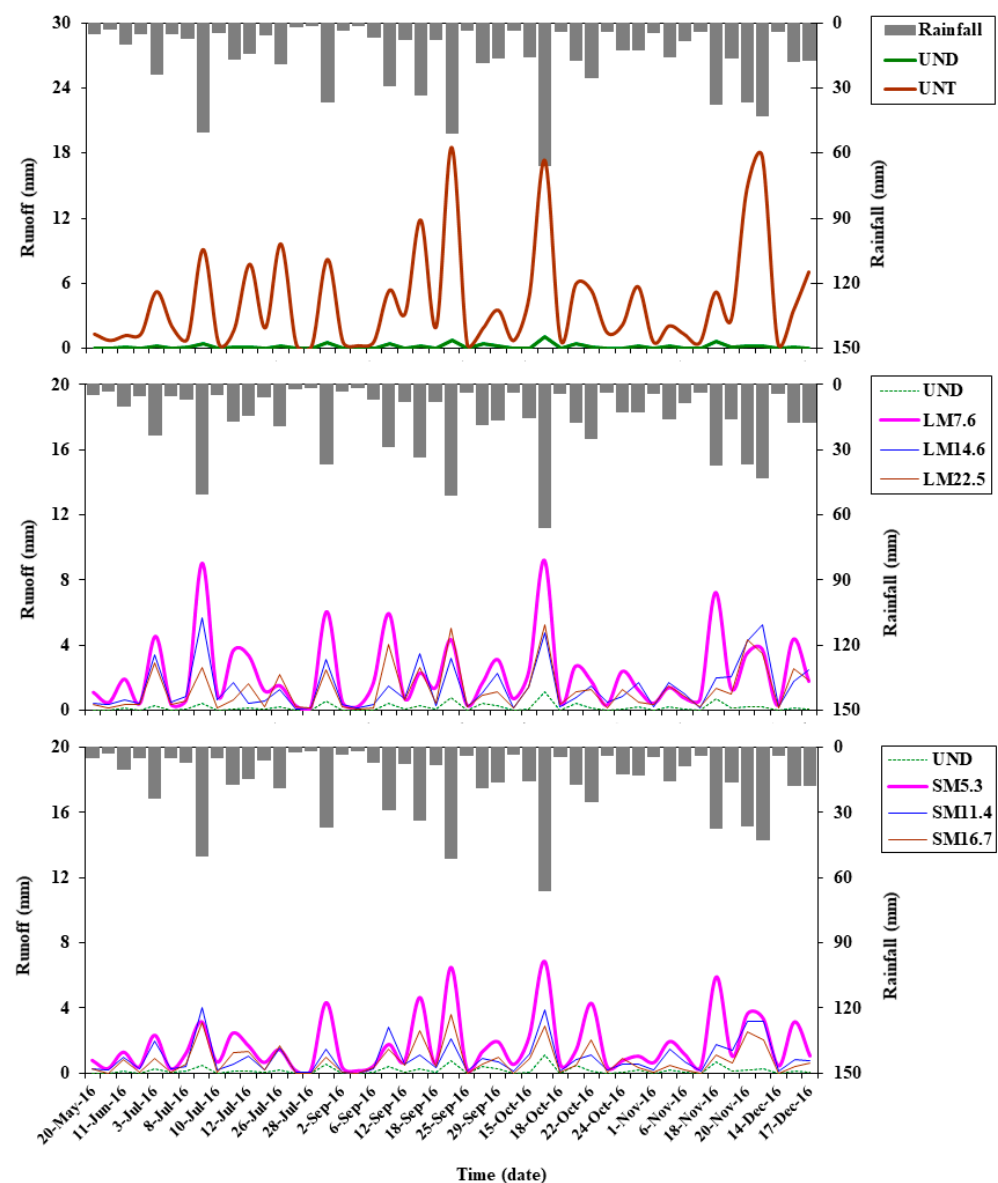


Figure 2. Runoff generated at the untreated skid trail (UNT), and undisturbed area (UND); litter mulch with three application rates (7.6, 14.6, and 22.5 Mg ha⁻¹) as LM7.6, LM14.6, and LM22.5; sawdust mulch (5.3, 11.4, and 16.7 Mg ha⁻¹) as SM5.3, SM11.4, and SM16.7 related to each corresponding rainfall event.

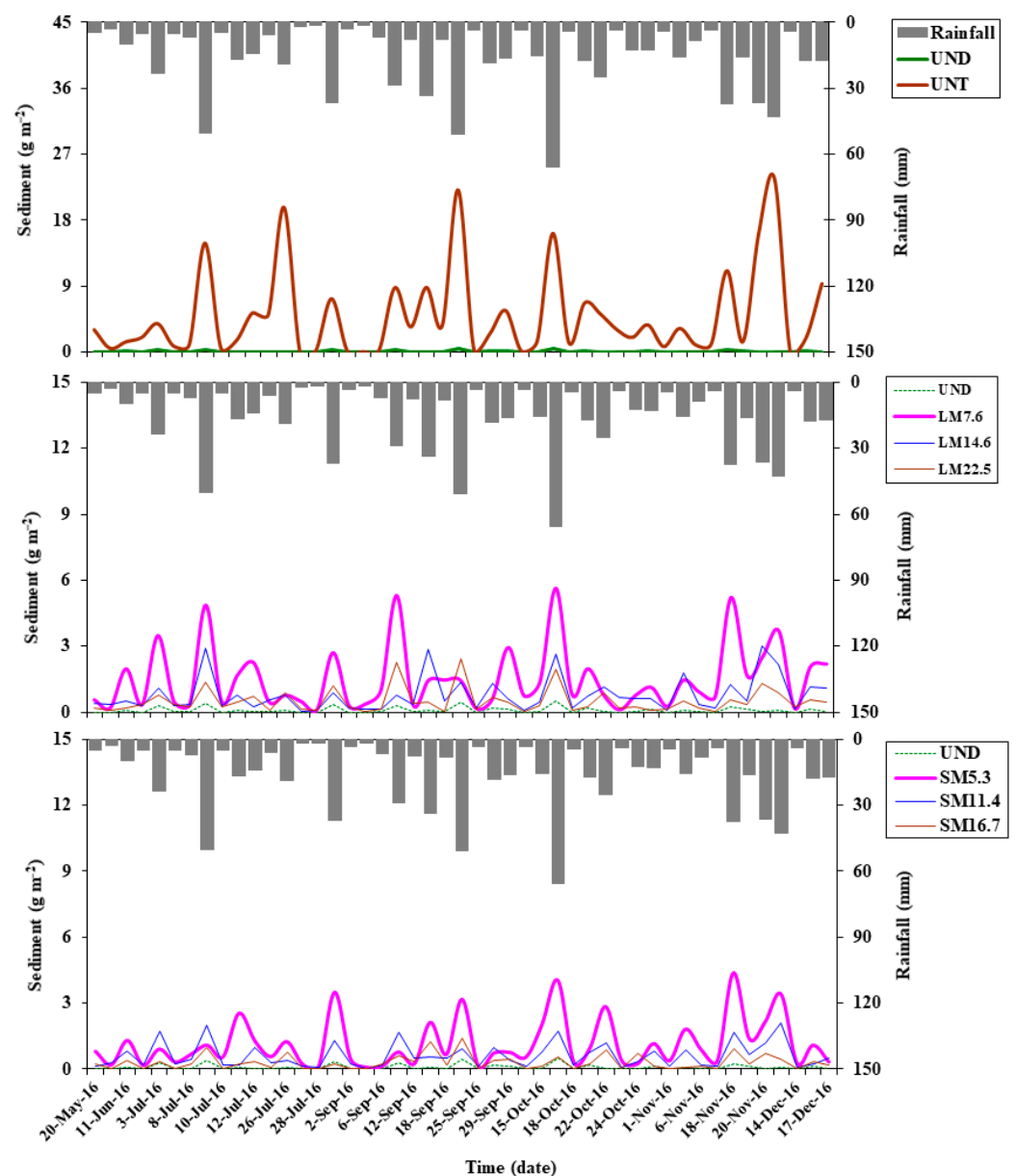


Figure 3. Sediment generated at the untreated skid trail (UNT), and undisturbed area (UND); litter mulch with three application rates (7.6, 14.6, and 22.5 Mg ha⁻¹) as LM7.6, LM14.6, and LM22.5; sawdust mulch (5.3, 11.4, and 16.7 Mg ha⁻¹) as SM5.3, SM11.4, and SM16.7 related to each corresponding rainfall event.

The runoff which occurred in the UNT (4.25 mm) was 25 times higher than the value of the UND plots. The LM7.6, LM14.6, and LM22.5 treatments significantly reduced the amount of runoff compared to the UNT at 2.22, 1.42, and 1.28 mm, respectively, indicating a decrease from 1.9 to 32.3 times compared to the UNT. The SM5.3, SM11.4, and SM16.7 treatments also significantly reduced the amount of runoff by 2.45 to 5.31 times compared to the UNT.

The results showed that the UND had the lowest and the UNT had the highest runoff coefficient among the different treatments. The runoff coefficient of the UNT was 24 times higher than the value of the UND. The runoff coefficient in the litter and sawdust mulches showed a decreasing trend as the application rate for both the litter and sawdust mulches increased. The runoff coefficients of the LM7.6, LM14.6, and LM22.5 treatments were 0.14, 0.09, and 0.07, respectively, and the runoff coefficients of the SM5.3, SM11.4, and SM16.7 treatments were 0.11, 0.05, and 0.04, respectively. According to Duncan's test, the runoff

coefficient in the LM14.6 and LM22.5 treatments and the SM11.4 and SM16.7 treatments were not significantly different.

The amount of sediment in the UNT was 55 times higher than the value of the UND. All treatments significantly reduced the amount of sediment. The LM7.6, LM14.6, and LM22.5 treatments reduced the amount of sediment by 1.51, 0.79, and 0.5 g m⁻², respectively, compared to the UNT. The sawdust treatments of SM5.3, SM11.4, and SM16.7 also reduced the amount of sediment to 1.14, 0.62, and 0.31 g m⁻², respectively. According to Duncan's test, the amount of sediment showed no significant difference between the LM22.5 and SM16.7 treatments (Figure 4).

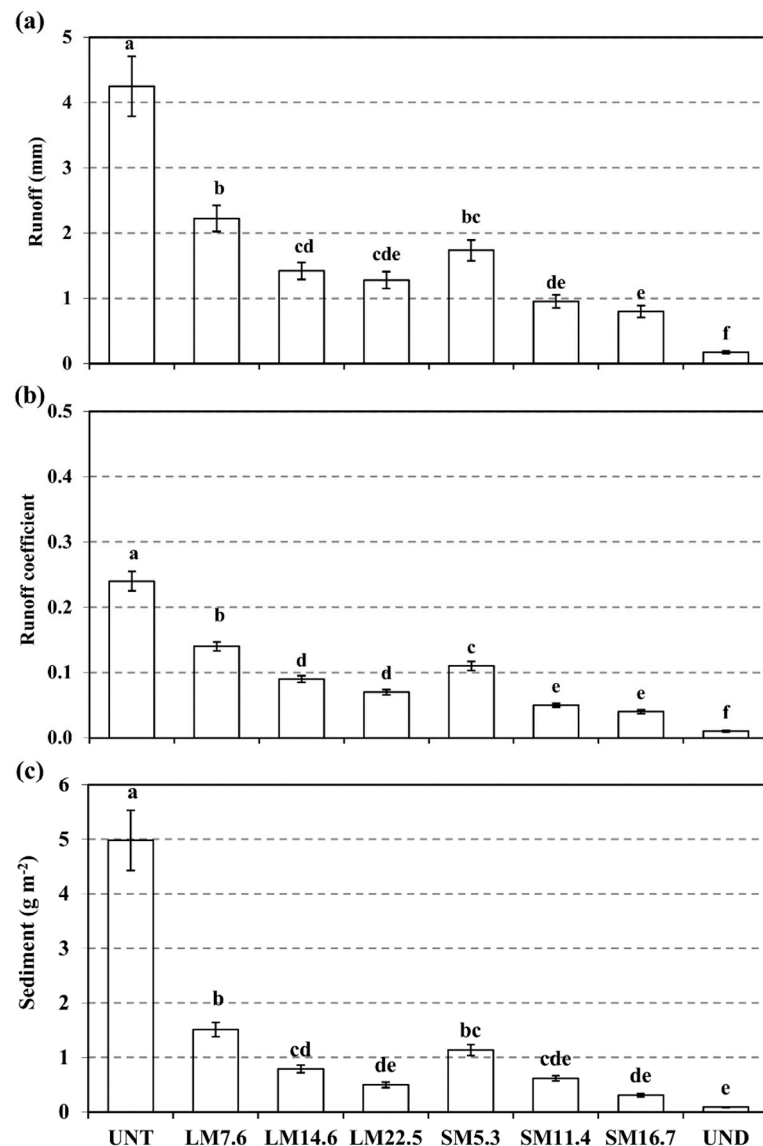


Figure 4. Average values of runoff (a), runoff coefficient (b), and sediment yield (c) in different treatments (litter mulch with three application rates (7.6, 14.6, and 22.5 Mg ha⁻¹) as LM7.6, LM14.6, and LM22.5; sawdust mulch (5.3, 11.4, and 16.7 Mg ha⁻¹) as SM5.3, SM11.4, and SM16.7; untreated skid trail (UNT); and undisturbed area (UND) after logging and mulching). Bars are means $\pm$ SD. Different lower-case letters on different columns indicate significant differences among the different treatments based on the Duncan test ($p < 0.05$).

3.2. Nitrate (NO₃-N) and Phosphate (PO₄-P) Concentrations

The oscillation of the nitrate with rainfall showed that the nitrate loss has a direct relationship with the amount of rainfall. In general, with the increase in rainfall, the

nitrate loss also increased in the UNT treatment. The highest nitrate loss in the UNT was 16.17 mg L^{-1} at the corresponding rainfall of 65.8 mm. LM7.6 had the highest nitrate loss of 6.82 mg L^{-1} at the rainfall event of 42.7 mm. LM14.6 at the rainfall event of 65.8 mm had the highest nitrate of 3.5 mg L^{-1} , and LM22.5 in the rainfall event of 36.3 mm had the highest nitrate loss of 2.84 mg L^{-1} . The highest value of nitrate loss for the SM5.3, SM11.4, and SM16.7 treatments were 3.93, 2.47, and 2.87 mg L^{-1} in rainfall events of 50.9, 50.9, and 42.7 mm, respectively (Figure 5).

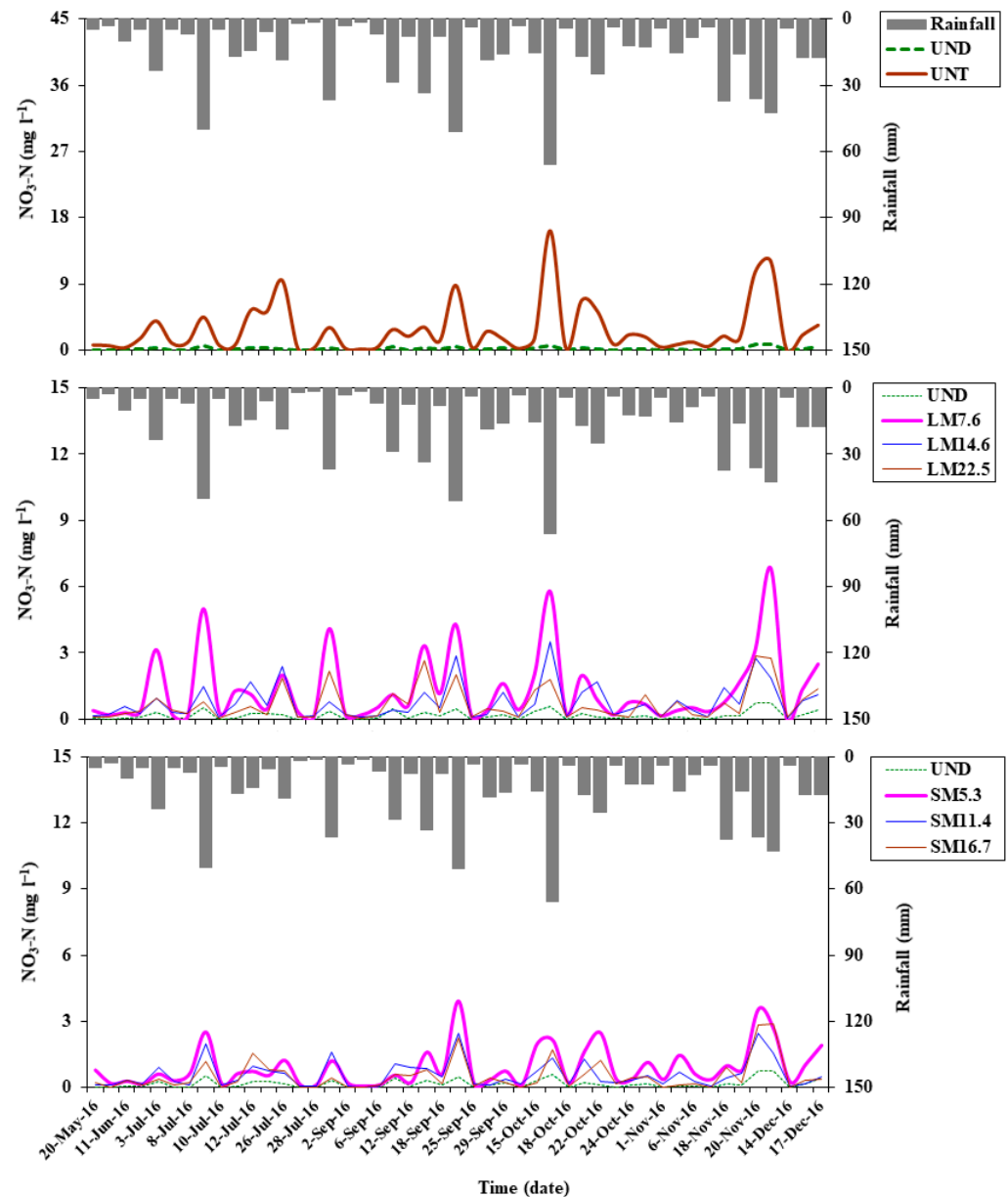


Figure 5. Nitrate generated at the untreated skid trail (UNT), and undisturbed area (UND); litter mulch with three application rates (7.6, 14.6, and 22.5 Mg ha^{-1}) as LM7.6, LM14.6, and LM22.5; sawdust mulch (5.3, 11.4, and 16.7 Mg ha^{-1}) as SM5.3, SM11.4, and SM16.7 related to each corresponding rainfall event.

The results showed a close fluctuation between rainfall events and phosphate loss in the UNT. The highest phosphate loss of 1.21 mg L^{-1} was observed in the UNT treatment at the rainfall of 50.9 mm. During the same period and a rainfall event of 42.7 mm, the highest amount of phosphate loss in the LM7.6, LM14.6, and LM22.5 treatments were 0.59, 0.34, and 0.28 mg L^{-1} , respectively. The highest phosphate loss under the SM5.3, SM11.4, and

SM16.7 treatments were 0.47, 0.26, and 0.27 mg L⁻¹, and the corresponding rainfalls of 42.7, 65.8, and 65.8, respectively (Figure 6).

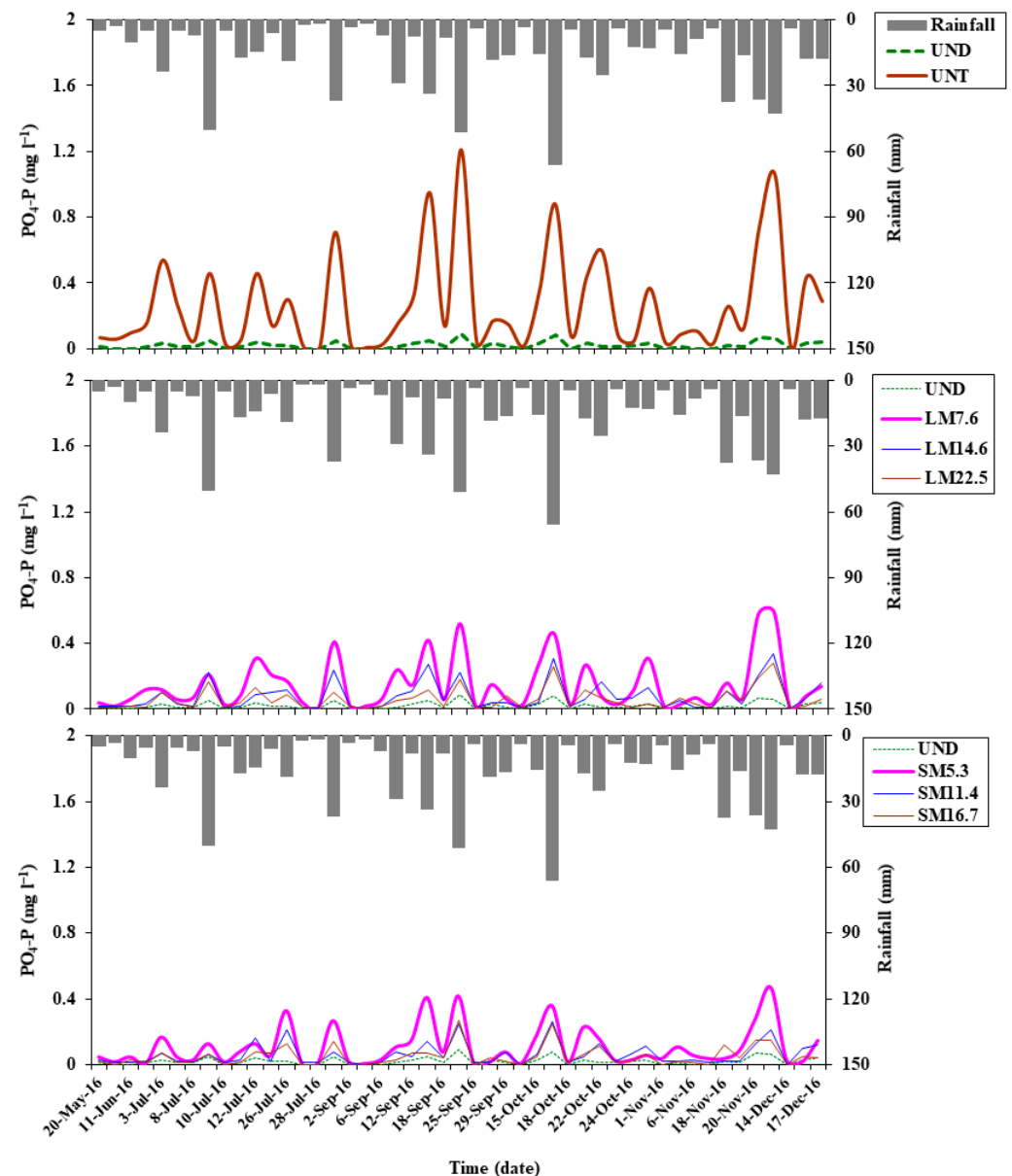


Figure 6. Phosphate generated at the untreated skid trail (UNT), and undisturbed area (UND); litter mulch with three application rates (7.6, 14.6, and 22.5 Mg ha⁻¹) as LM7.6, LM14.6, and LM22.5; sawdust mulch (5.3, 11.4, and 16.7 Mg ha⁻¹) as SM5.3, SM11.4, and SM16.7 related to each corresponding rainfall event.

The results showed that the nitrate loss in the UNT was 16 times higher than the value of the UND by 2.74 mg L⁻¹. All the treatments significantly reduced nitrate loss, so the LM7.6 had the smallest effect with a 2-fold reduction, and the SM16.7 with a 5-fold reduction had the greatest effect on reducing nitrate loss compared to the UNT. The amount of nitrate loss in the LM7.6, LM14.6, and LM22.5 treatments were 1.36, 0.78, and 0.69 mg L⁻¹, respectively. Further, the nitrate loss values for the SM5.3, SM11.4, and SM16.7 treatments were 0.94, 0.58, and 0.52 mg L⁻¹, respectively. According to Duncan's test, nitrate loss did not significantly differ at the LM14.6, LM22.5, and SM11.4 treatments.

Phosphate loss in the UNT was 13.5 times higher than the value of the UND. The UND had the lowest and the UNT had the highest amount of phosphate loss. LM7.6, which

had the smallest effect, reduced the loss of phosphate from 0.27 mg L^{-1} to 0.15 mg L^{-1} compared to the UNT, and the SM16.7 treatments, which had the greatest effect, reduced this amount to 0.05 mg L^{-1} . The results showed that the phosphate loss decreased in the litter and sawdust mulches as the application rate increased. According to Duncan's test, the value of phosphate loss at both the LM22.5 and SM11.4 treatments were not significantly different (Figure 7).

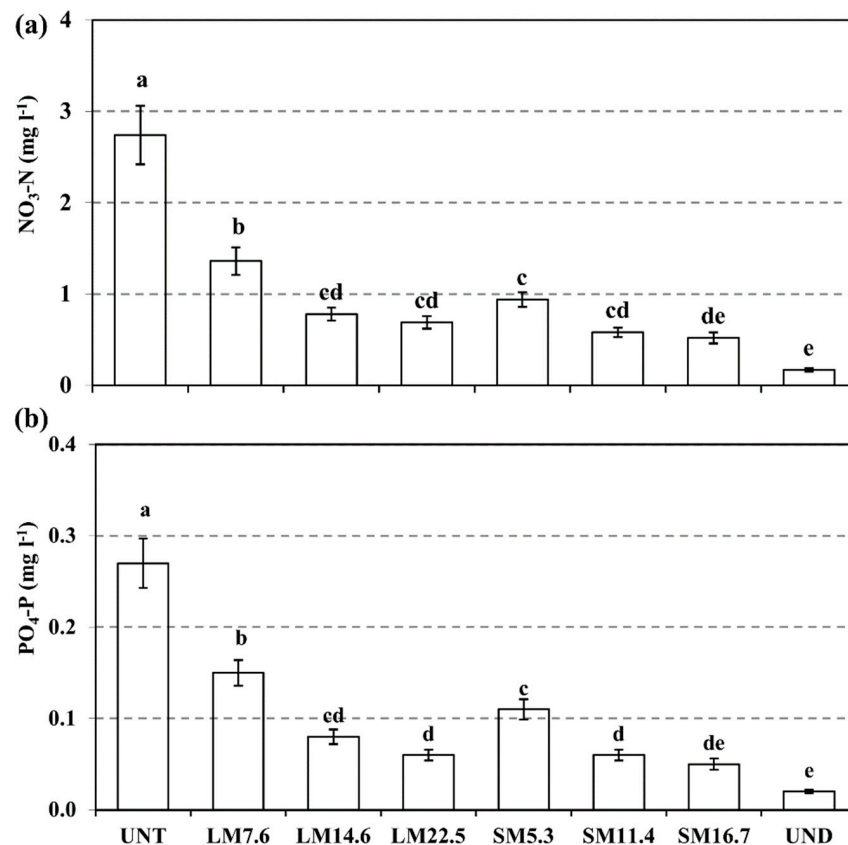


Figure 7. Average values of nitrate (a) and phosphate (b) in different treatments (litter mulch with three application rates (7.6, 14.6, and 22.5 Mg ha^{-1}) as LM7.6, LM14.6, and LM22.5; sawdust mulch (5.3, 11.4, and 16.7 Mg ha^{-1}) as SM5.3, SM11.4, and SM16.7; untreated skid trail (UNT); and undisturbed area (UND)) after logging and mulching. Bars are means $\pm$ SD. Different lower-case letters on different columns indicate significant differences among the different treatments based on the Duncan test ($p < 0.05$).

3.3. Rainfall and Soil Properties

During the studied period, a total number of 43 rainfall events $> 2 \text{ mm}$ were measured. During this same period, 747.2 mm of rainfall was recorded and averaged at 15.9 mm per event (ranging from 1.5 to 65.8 mm).

The results showed that the lowest soil bulk density and the highest level of total porosity, organic matter, and litter depth were detected under the UND treatment, which significantly differed from the other treatments. The canopy cover and soil particle distribution did not significantly differ among the treatments (Table 1).

The results of Spearman's correlation analysis showed that phosphate has a positive correlation with nitrate, sediment, runoff, and the runoff coefficient, and has a negative correlation with soil organic matter. Nitrate has a positive correlation with sediment, runoff, and the runoff coefficient, and has a negative correlation with soil organic matter. The runoff coefficient has a positive correlation with sediment and runoff and, at the 95% confidence level, with the soil bulk density, and also has a negative correlation with the total soil porosity, soil organic matter, and litter depth. Also, sediment has a positive correlation

with runoff. The soil bulk density has a negative correlation with the total soil porosity, litter depth, and soil organic matter, and the total soil porosity has a positive correlation with the soil organic matter and the litter depth (Figure 8).

Table 1. Average values of soil characteristics in the studied treatments. Different letters after means within each treatment indicate significant differences based on Duncan's test ($p < 0.05$).

Treatment	Characteristics							
	Bulk Density (g cm ⁻³)	Total Porosity (%)	Organic Matter (%)	Litter Depth (cm)	Canopy Cover (%)	Sand (%)	Silt (%)	Clay (%)
UNT	1.30 ± 0.04a	49.8 ± 1.5b	3.4 ± 0.4b	0b	84.7 ± 2.5a	41.3 ± 9.3a	40.3 ± 4.5a	18.3 ± 4.9a
LM7.6	1.29 ± 0.03a	50.5 ± 1.2b	3.4 ± 0.4b	0b	82.7 ± 4.7a	30.0 ± 2.0a	45.3 ± 3.2a	24.7 ± 1.5a
LM14.6	1.30 ± 0.04a	49.8 ± 1.5b	4.1 ± 0.6b	0b	81.7 ± 3.2a	35.0 ± 5.0a	40.3 ± 4.7a	24.7 ± 1.5a
LM22.5	1.30 ± 0.06a	50.0 ± 2.3b	4.0 ± 0.3b	0b	82.7 ± 3.5a	29.7 ± 3.5a	46.3 ± 2.5a	24.0 ± 1.0a
SM5.3	1.31 ± 0.05a	49.5 ± 1.8b	3.2 ± 0.8b	0b	83.7 ± 2.5a	34.3 ± 5.0a	40.7 ± 4.0a	25.0 ± 3.0a
SM11.4	1.29 ± 0.05a	50.3 ± 1.7b	3.7 ± 0.6b	0b	81.7 ± 8.1a	39.0 ± 5.6a	40.3 ± 3.2a	20.7 ± 4.2a
SM16.7	1.31 ± 0.05a	49.5 ± 1.8b	3.8 ± 0.6b	0b	84.3 ± 4.6a	41.3 ± 5.1a	39.0 ± 9.5a	19.7 ± 4.9a
UND	0.94 ± 0.05b	63.8 ± 1.8a	9.9 ± 0.6a	6.2 ± 0.8a	83.0 ± 6.2a	39.7 ± 4.0a	40.0 ± 7.9a	20.3 ± 4.7a

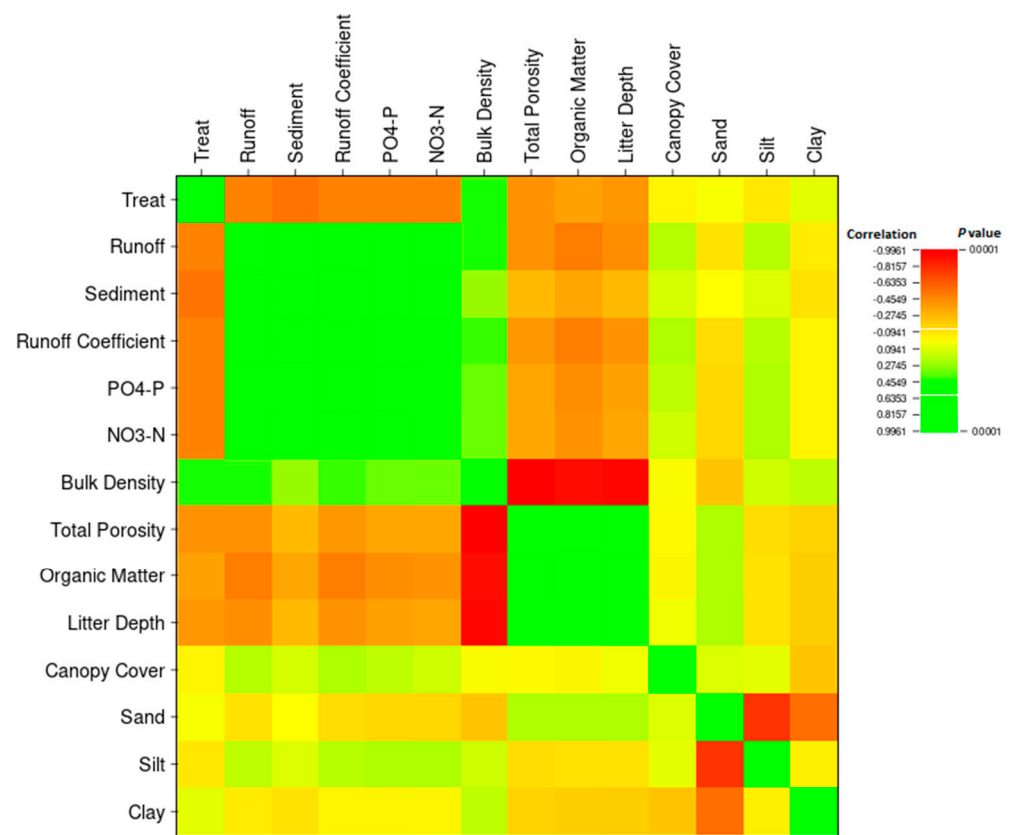


Figure 8. Spearman correlation (heat map) between treatment, runoff, sediment, runoff coefficient, nitrate, phosphate, litter depth, canopy cover, and soil in the different treatments.

4. Discussion

Skid trails, as a consequence of compacted soil, are known to represent zones characterized by high runoff amounts [64–66]. However, the situation returns to the pre-harvesting conditions in a short time through the establishment of herbaceous species and natural regeneration, and thanks to the progressive closing of the canopy gaps occurring after the implementation of silvicultural intervention [8]. The results confirmed this aspect with the untreated trails (UNTs), which presented very high values of runoff as well as sediment and nutrient loss in comparison to the other experimental treatments.

The implementation of best-management practices to restore the skid trails and allow for a reduction in the amounts of runoff and nutrient loss is therefore fundamental in the

view of sustainable forest management [67]. In this framework, the hypothesis that litter and sawdust can act as efficient mulching options to decrease erosion and nutrient loss from the skid trails was largely confirmed (Figures 2–7). All the studied parameters were reduced by more than half, even with the lowest rate of mulching application, for both litter and sawdust. Mulching with litter and sawdust effectively prevented soil erosion and sediment runoff. It also caused the absorption of the suspended sediments from water, which minimized the movement of soil particles to the downslope. Mulching with sawdust and litter was confirmed to be an effective low-cost solution for decreasing the negative impacts of ground-based forest operations [68]. Previous studies have revealed that applying organic mulches such as sawdust and litter could significantly augment surface soil from raindrop impacts, improve surface roughness, increase water infiltration, diminish soil particle detachments and surface water flow, and decrease soil loss [52,53,58]. However, this study found that erosion and nutrient loss are still lower in the undisturbed soil (UND) than in any experimental treatment. This can probably be related to the higher organic matter content that is present in the UND treatment (Table 1 and Figure 8). A high value of organic matter in the soil is able to increase the water-holding capacity and soil permeability, thus decreasing the runoff volume [69]. Previous studies have also highlighted the importance of soil organic matter in preventing soil erosion [8], mostly by improving the soil structure [41] and preventing the collapse of soil aggregates [70].

The second research hypothesis, stating that sawdust is more effective than litter as a mulching material, was only partially confirmed. The greater efficacy of sawdust than litter on the surface of skid trails can be attributed to the higher density of sawdust mulches. These tend to stick together and remain placed on top of each other due to the impact of raindrops where less movement occurs. The litter, however, has a lower density and is moved by the force of the wind and the strikes of the raindrops. It is arranged in a standing shape and provides less coverage. In addition, sawdust has more lignin than leaves and has a longer life on the logging road, unlike litter, which decomposes earlier and has a shorter duration than sawdust [70]. These results were found only for the lowest application amount, while at higher mulching rates, the differences between the two materials were not statistically significant. Therefore, we can recommend the application of sawdust in the cases where low amounts of mulching material are available, while both solutions are equally valid where there is no shortage of either sawdust or litter.

Finally, the third research hypothesis was also partially confirmed. The results did not reveal a linear correlation between the amount of mulching application and decreased erosion for both litter and sawdust. This finding is particularly important from the perspective of the cost-effectiveness of the mulching application, in terms of saving both manpower and supply costs. From the findings, it seems that about 15 Mg ha^{−1} of litter and about 11 Mg ha^{−1} of sawdust are enough to strongly reduce erosion, while higher amounts do not lead to any significant improvement.

Concerning the possible study limitations, it is worth highlighting that this represents a case study, with findings which could be limited to the specific context of the investigated study area. However, the obtained results are clear and can serve as a basis for implementing larger field trials and meta-analytical studies on this important issue.

Finally, the authors would like to point out the importance of carrying out studies dealing with the economic evaluation of the implementation of different kinds of mulch, including, for instance, the assessment of transport and application costs. This issue was outside the scope of the present manuscript, but should represent a further step in the research in the topic. In detail, time–motion studies regarding the application phase of the mulching, as well as an economic evaluation of the logistics of the supply chains for the various mulching types, should be developed. This kind of research will help to shape detailed and effective policy recommendations on which mulching types are more effective, both from the environmental and economic points of view.

5. Conclusions

In the present study, the authors investigated the efficacy of organic mulches on runoff as well as soil and nutrient loss (nitrate and phosphate) on skid trails under natural rainfall conditions, including litter mulch, with three application rates of LM7.6, LM14.6, and LM22.5; sawdust mulch as SM5.3, SM11.4, and SM16.7; untreated skid trails (UNTs); and undisturbed areas (UNDs) in the Hyrcanian forest. The findings confirmed that the application of surface covers during and after logging operations can be effective in preventing soil loss and determining the runoff amount and quality. The main outcomes of this study are the following:

- Both litter and sawdust are effective mulching options to reduce erosion and nutrient loss from skid trails;
- Sawdust was more effective than litter;
- For both litter and sawdust, increasing the application rates led to decreased erosion and nutrient loss;
- The mulching application rates of 7.6–14.6 Mg ha^{−1} and 5.3–11.4 Mg ha^{−1} for litter and sawdust, respectively, were revealed to be the best solutions to alleviate adverse effects and to maintain soil and water conservation after logging operations on skid trails.

We therefore recommend the application of these mulching materials in the case of their local availability, in order to decrease the negative environmental concerns of forest operations. Future studies should be focused on an economic evaluation of the application of mulching, in order to also understand the feasibility from the point of view of the economic and social sustainability of this forest restoration approach. In this case, economic evaluations will lead to satisfactory results; we recommend the inclusion of applications of sawdust and litter mulching as best-management practices in the forest regulation of the study area.

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