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Analysis of Surface Deformation and Physical and Mechanical Parameters of Soils on Selected Skid Trails in the Gorce National Park

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Abstract: Skidding is considered to be one of the most stressful works for the forest environment. This paper presented the results obtained from the analysis of soil deformation and selected physical and mechanical parameters of soils on skid trails in the Gorce National Park. The study analyzed two horse and tractor skid trails that are in continuous use in the park. Measurements of parameters were recorded before (summer) and after (autumn) a total of 81 skidding cycles, using a profilometer and a penetrometer, and soil samples were collected for analysis. The measurements obtained from the horse trails indicated that soil compactness was considerably higher in the lower sections of the trails and on the side more loaded by horse traffic and the transported load, which was related to the trail course in the field. The values of penetration resistance were high in the middle of those trails, reaching 6.8 MPa in the layer up to 10 cm. In the tractor trail the values of soil compactness reached 7.62 MPa in the layer up to 10 cm deep and were similar across the width of the trail and deep into the soil profile, with only slight changes observed in the monitored period. As a result of skidding, there were increases in the maximum depth of ruts reaching up to 4.6% on horse trails and up to 10.8% on tractor trails. Soil erosion per 10 m of trail caused by skidding and other natural factors during the study reached 1.314 and 0.390 m^3 for the tractor and horse trail, respectively, wherein volume of skidded wood on the tractor trail was 180.1, and 18.1 m^3 on horse trails. This confirms that the volume of eroded soil on the trails is determined by the type of skidder used and volume of skidded wood, so it is important to choose the right kind of skidder based on the conditions in which the skidding work will be carried out.

Keywords: mountain forests; mechanical skidding; horse skidding; surface erosion; protected areas

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1. Introduction

Skid trails are an important element of forest management, which allow the harvested timber to be transported from the interior of stands to storage areas and further to recipients [1,2]. In lowland areas characterized by the logging mode of forest management, there is no need to designate trails, whereas in clear-cutting and clear-felling, as well as in mountainous areas, it is necessary to have temporary or permanent skid trails. Designating trails in the field limits potential damage to the stand remaining and erosion damage to the strips of land where trails will be located [2–4]. Trails must also exist in the stands where typical forest management is not performed, such as those under active protection inside national parks. In these stands, only limited economic activities related to sanitary cuts are carried out, for example, removal of trees colonized by bark beetles (*Scolytinae*), which affects the growth of their population [5,6]. In Poland, massive weakening of spruce (*Picea*) populations and associated damage of a gradational nature caused by bark beetles were first reported in the Sudetes, and have been currently observed in the Carpathians and other regions [7,8]. This is especially a major problem in the case of commercial forests, including the protected ones. This results in a large harvest of spruce "bark beetle" wood, accompanied by the occurrence of erosion damage on skid trails [9–11]. The phenomenon of erosion on skid trails, and its dynamics related to trail use, is also an important issue of soil conservation [12,13]. A skid trail is defined as a strip of land inside a stand, devoid of woody vegetation and undergrowth, on which a stage of timber transport is realized from the trunk to the depot, with given technical parameters (in advanced cases, the parameters include longitudinal slope, transverse slope, surface, and radii of horizontal and vertical bends). In the stand, trails exist in the form of a network with a certain density resulting from the distance between them, which in turn is influenced by the way the forest is managed and the felling cuts are used, as well as by the age of the stands thus made available [1,14,15]. Three main factors cause erosion damage on skid trails: the movement of skidding vehicles, the dragging of timber along the surface of the trail, and surface runoff [16]. Erosion damages resulting from skidder traffic primarily include shearing, mixing, and compaction of the substrate in the trail surface layer. These damages are caused by the movement of all types of skidding means, and their magnitude is determined by the type of means (horse or tractor) [17–19]. Heavy tractors consisting of narrow and high-pressure tires cause the most damage to skid trails [20], and thus the associated damage can be reduced by using lighter tractors with wide and low-pressure tires [21] or by using tracked vehicles [17]. The size of erosion damage resulting from dragged wood depends on the skidding method used (dragged, semi-forwarding), and the end of the log by which the wood is skidded (thinner or thicker) [22]. The highest damage is caused by dragged skidding by the thicker end, while less damage results from semi-forwarding skidding, and these can be reduced by using shields of the timber skid (sliding disks or caps). In addition to moving down the slope and to the sides, the soil stripped by skidding is locally compacted, which reduces the infiltration capacity of rainwater into the soil profile [23,24], thereby creating favorable conditions for surface runoff [25]. Abundant surface runoff on steeply sloping trails is characterized by a high uplift force and easily transports loose, detached material down the slope. This may lead to significant losses of soil in the trail cross section, although local, more or less temporary soil gains can be observed in the cross section and soil is either "deposited" due to the loss of uplift force by surface runoff or "pushed aside" to the sides of the main wood drag channel [26,27]. Studies have indicated that erosion damage is intensified if skidding operations are performed when the soil moisture is high [28,29]. This is due to the much lower shear strength of soil under such conditions [30]. Surface runoff-related erosion damage can be reduced by surface drainage of the trail (lateral falls, waterfalls), shortening sections without surface drainage, reducing longitudinal falls, frequent maintenance of the drainage system to ensure the system is in working order, and avoiding skidding works when the soil moisture in the trails is high [23]. However, most of the skid trails are found without any engineering or antierosion preparation. The period of functionality of such trails usually lasts from a few to several years, and depends directly on the intensity of use as well as the physiographic conditions of the slope. After their utility values are lost, these trails are abandoned. Antierosion development of depleted or abandoned skid trails, supporting the inundation of erosion slope cuts, is a rarity [31,32].

The areas within the active protection zone of the Gorce National Park are an important part of natural heritage; hence, it is necessary to understand how they are affected by the execution of logging works. This study aimed to determine the dynamics of soil deformation changes and some physical and mechanical parameters of soil on selected skid trails in the active protection zone of this park, in the context of logging works carried out for nature protection.

2. Materials and Methods

Measurements of parameters were taken in the part of the Gorce National Park outside the areas of strict protection, where it is possible to carry out forest management to some extent, including works to remove trees attacked by bark beetles and to limit the extent of further damage to the stands of the park [33]. The research was conducted in two sections—129 and 130—located at an altitude of about 880–920 m above sea level, in the eastern part of the Gorce National Park, in Turbacz Protective District, on the fragments of skid trails with a natural ground surface (Figure 1). Two permanently used horse trails in section 130 (Ht130) (4 years old, ca. 430 m long, volume of skidded wood before measurement ca. 40 m^3), and section 129 (Ht129) (3 years, ca. 380 m, ca. 20 m^3), as well as a tractor trail in section 129 (Tt129) (8 years, ca. 900 m, ca. 1200 m^3), were selected for the study. The area of section 129 is 31.61 ha [49°33′41.706″ N 20°13′11.358″ E], and that of section 130 is 130–131.65 ha [49°33′33.014″ N 20°12′58.493″ E]. The bark beetle wood harvested on the trails was removed to a collection trail and further transported along a slope road to the Kamienica valley. On each of the selected trails (Ht129, Ht130, Tt129), the measurements were recorded on two sections: upper (U) and lower (L) (Table 1).

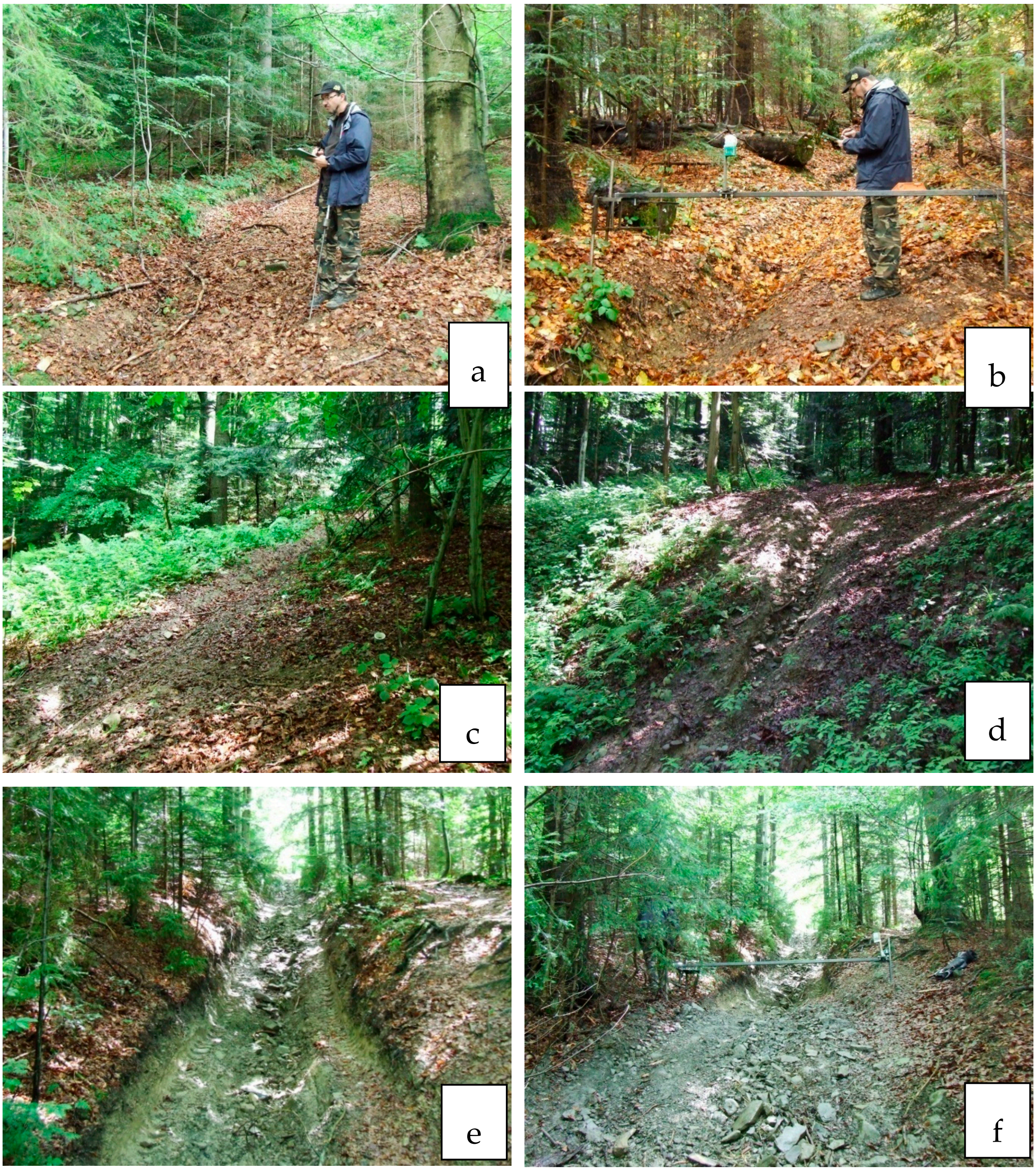


Figure 1. Photographs of the sections of skid trails selected for the study: (**a**) Ht129U, (**b**) Ht129L, (**c**) Ht130U, (**d**) Ht130L, (**e**) Tt129U, and (**f**) Tt129L.

Table 1. Characteristics of the trails and study area.

Trail	Ht129U	Ht129L	Ht130U	Ht130L	Tt129U	Tt129L
Slope	28.8%	26.4%	33.4%	29.4%	11.4%	11.3%
Habitat type	Fresh mixed mountain forest					
Stand Abundance, age	5 beech, 3 fir, 2 spruce 255 $m^3 \cdot ha^{-1}$; 110 years		8 beech, 1 spruce, 1 fir 311 $m^3 \cdot ha^{-1}$; 130 years		5 beech, 3 fir, 2 spruce 255 $m^3 \cdot ha^{-1}$; 110 years	
Undergrowth	Lack		Braun's holly fern *Polystichum braunii* (Spenn.)		Lack	
Granulometric composition [34]	Sa/Si/Cl [%] 70.3/25.0/4.7	Sa/Si/Cl [%] 71.8/24.1/4.1	Sa/Si/Cl [%] 68.2/26.8/4.7	Sa/Si/Cl [%] 68.7/26.3/5.1	Sa/Si/Cl [%] 48.0/43.0/9.0	Sa/Si/Cl [%] 59.6/33.9/6.4
Soil type	Leached brown					

A John Deere 2140 Turbo 4 × 4 universal tractor (60.31 kW, 3790 kg) with a Fransgard V 6500 rope winch (pulling force 6.5 t, weight without rope 400 kg) was used on the tractor trail. Measurements on trails were made on two dates: 29 July 2015 (T1) and 22 October 2015 (T2). Between these dates, 198.2 m^3 of wood was skidded on the trails (Table 2). On days 1, 2, and 3 before the measurements, the total rainfall at T1 was 1.2, 1.2, and 2.2 mm, while at T2 it was 5.5, 13.5, and 13.5 mm, respectively.

Table 2. Skidding intensity in the study area between dates T1 and T2 (Gorce National Park data).

Skid Trail	Number of Loaded Transport Passes (3 Months)	Average Volume of a Single Wood Load [m^3]	Total Volume of Skidded Wood [m^3]
Ht129	20	0.6 ± 0.04	12.1
Ht130	10	0.6 ± 0.02	6.0
Ht129	51	3.5 ± 0.30	180.1

The following parameters were determined on selected sections of the trails: soil deformation (using a laser profilometer); penetration resistance *PR* (using a penetrometer) up to 30 cm depth; and dry bulk density *BD* and moisture content *MC* of the soil samples taken from the layer up to 10 cm depth (calculations based on the results of weighing before and after drying samples at 105 °C for 24 h with an accuracy of ±0.1 g; measuring cylinders, $V = 250$ cm^3) [35]. Penetration resistance (compactness) *PR* (three repetitions) and soil samples (three repetitions) were also measured at control sites on the left and right side of the trails (Contr), at load dragging sites in rut (R), at tractor wheel passing (Tt129), left rut (LR) and right rut (RR) sides, or horse moving from the load dragging sites (Ht129 and Ht130) (Figure 1). The profilometer (Figure 1b,f) mapped the vertical profile of a trail up to 2.8 m wide, cleared of leaves and other loose parts of vegetation. The profile was measured every 5 cm, along the instrument beam, leveled and positioned perpendicular to the longitudinal axis of the trail, at three positions (PI, PII, PIII) which were 0.25 m apart (Figure 2). At each measurement location of the profile, the points where the profilometer supports were set at time one (T1) were marked for resetting at time two (T2). Each point marked on the profile had coordinates [x, y, z], where x is the position of the rangefinder along the instrument beam (0–2.8 m, in 0.05-m increments), y is the position of PI, PII, and PIII profile (0, 0.25, and 0.5 m, respectively), and z is the vertical distance of the ground to the instrument beam (up to 2 m ± 3 mm). For each of the two displacement points on the profilometer at T1 and their corresponding points at T2 with respect to coordinates x and y, the areas of the resulting grid were calculated and the change in the rut profile at T2 relative to T1 was determined from the grid. To calculate the volumes of ruts as well as the changes in volume at T2 relative to T1, for both adjacent profiles (PI and PII, PII and PIII) the calculated areas were averaged and multiplied by the distance between the cross sections. The component volumes calculated for the successive points of displacement of the rangefinder along the profilometer beam were summed and expressed in m^3, and then recalculated for a trail length of 10 m.

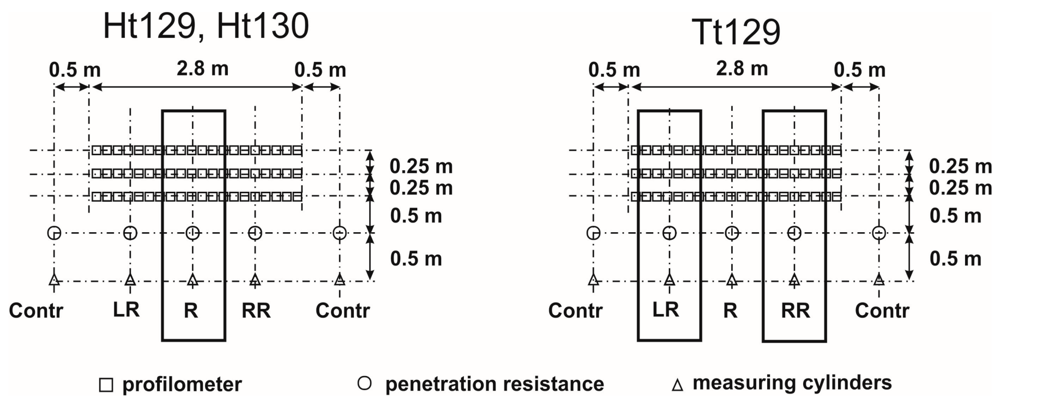
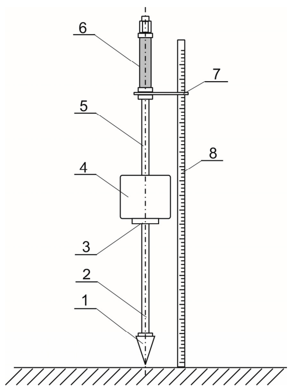


Figure 2. Scheme of making measurements on horse (Ht129, Ht130) and tractor (Tt129) skid trails.

Penetration resistance (compactness) *PR* was measured to a depth of 30 cm using an impact penetrometer (Figure 3) [36]. In this instrument, the penetration of the cone (1) attached to the introductory rod (2) was facilitated by a freely falling weight (4), along the guide (5), which hit the bumper (3). The measurement consisted of repeated manual lifting of the weight (4) and lowering it along the guide (5), holding the penetrometer by its handle (6). Each time the cone penetrated the soil, the distance between the ground level and the indicator (7) was measured with the linear gauge (8) ($\pm$1 mm).



(**a**)

(**b**)

Figure 3. Cone impact penetrometer: (**a**) scheme of the penetrometer: 1—cone, 2—introductory rod, 3—bumper, 4—weight, 5—guide, 6—handle, 7—indicator, and 8—linear gauge; (**b**) penetrometer measurements in the field (photo: Rygalik).

The penetrometer had a cone with a base diameter of D = 2.03 cm, an opening angle of α = 30° [37], and a weight of m = 2 kg. Penetration resistance *PR* was determined from the measurements based on the method proposed by Harrick and Jones [36]. The calculated values of compactness were then averaged at three levels (p1: 0–10 cm, p2: 10.1–20 cm, p3: 20.1–30 cm), for each trail section (Table 1) and measurement location (LR, R, RR, Contr). Similarly, the values of moisture content and bulk density were averaged for depths up to 10 cm. Using an analysis of variance, for each depth, trail, and measurement date, the mean values of compactness, bulk density, and moisture content were compared for different measurement locations (LR, R, RR, Contr) (Table 1). This was followed by Fisher's least significant difference (LSD) test to distinguish homogeneous groups.

3. Results

3.1. Moisture Content and Bulk Density of Soil

It was observed that at both sections of horse and tractor trails (LR, R, and RR) and at sites next to the trails (Contr), the average soil moisture (Table 3; Figure 4a) determined at T2 was generally higher than that determined at T1. However, this was not the case with Ht130L, Ht130U, and Ht129L, which may have been due to the distance between sections 129 and 130 where the trails were located (different altitudes), tree canopy, and uneven horizontal distribution of precipitation in the area [38]. Along the skid trail (LR, R, RR) on the horse trails (Ht129, Ht130), moisture content was lower compared to the average values recorded in the control (Contr), while at the load dragging site (R) (in depressed terrain) the content was generally higher compared to the sites next to it (LR and RR), except for Ht130U at T1. On the tractor trail in Tt129L, moisture content was higher in the control (Contr) than on the skid trail (LR, R, RR), while in the case of Tt129U the highest moisture content was recorded at the load dragging site (R).

Table 3. Mean (±SD) current soil moisture and dry bulk density in trails and control plots (superscript a–d: homogeneous groups determined by Tukey's test, $p < 0.05$).

Trail	Date	Moisture *MC* ($g \cdot g^{-1}$)				Dry Bulk Density *BD* ($g \cdot cm^{-3}$)			
		LR	R	RR	Contr	LR	R	RR	Contr
Ht129U	T1	0.462 ^{a} ±0.37	0.435 ^{b} ±0.038	0.450 ^{c} ±0.040	0.499 ^{d} ±0.036	0.880 ^{b} ±0.062	1.123 ^{d} ±0.080	0.973 ^{c} ±0.069	0.692 ^{a} ±0.049
	T2	0.660 ^{a} ±0.053	0.471 ^{b} ±0.044	0.728 ^{c} ±0.058	0.670 ^{a} ±0.054	0.840 ^{b} ±0.060	1.083 ^{c} ±0.077	1.010 ^{c} ±0.062	0.678 ^{a} ±0.048
Ht129L	T1	0.416 ^{a} ±0.04	0.465 ^{b} ±0.042	0.466 ^{b} ±0.039	0.499 ^{c} ±0.040	0.872 ^{b} ±0.062	0.980 ^{c} ±0.070	0.943 ^{c} ±0.067	0.631 ^{a} ±0.045
	T2	0.384 ^{a} ±3.1	0.557 ^{b} ±0.050	0.678 ^{c} ±0.061	0.590 ^{d} ±0.047	0.896 ^{b} ±0.055	1.011 ^{c} ±0.062	0.978 ^{c} ±0.069	0.662 ^{a} ±0.047
Ht130U	T1	0.660 ^{a} ±0.053	0.471 ^{b} ±0.038	0.728 ^{c} ±0.058	0.670 ^{a} ±0.054	0.878 ^{b} ±0.054	1.028 ^{c} ±0.063	1.014 ^{c} ±0.062	0.673 ^{a} ±0.046
	T2	0.366 ^{a} ±0.033	0.635 ^{b} ±0.006	0.422 ^{c} ±0.004	0.525 ^{d} ±0.042	0.838 ^{b} ±0.051	0.988 ^{c} ±0.060	1.026 ^{c} ±0.063	0.651 ^{a} ±0.048
Ht130L	T1	0.386 ^{a} ±0.035	0.546 ^{c} ±0.005	0.391 ^{a} ±0.004	0.491 ^{b} ±0.039	0.889 ^{b} ±0.063	1.045 ^{c} ±0.064	1.020 ^{c} ±0.062	0.685 ^{a} ±0.042
	T2	0.344 ^{a} ±0.031	0.468 ^{b} ±0.006	0.456 ^{b} ±0.005	0.519 ^{c} ±0.042	0.849 ^{b} ±0.060	1.005 ^{c} ±0.071	1.052 ^{c} ±0.075	0.669 ^{a} ±0.041
Ht129U	T1	0.533 ^{d} ±0.029	0.127 ^{a} ±0.048	0.165 ^{b} ±0.003	0.325 ^{c} ±0.026	1.300 ^{b} ±0.108	1.345 ^{c} ±0.082	1.379 ^{c} ±0.097	0.741 ^{a} ±0.045
	T2	0.591 ^{d} ±0.032	0.161 ^{a} ±0.053	0.187 ^{b} ±0.023	0.363 ^{c} ±0.029	1.276 ^{b} ±0.112	1.305 ^{c} ±0.088	1.379 ^{c} ±0.103	0.717 ^{a} ±0.051
Ht129L	T1	0.130 ^{a} ±0.018	0.137 ^{a} ±0.025	0.131 ^{a} ±0.018	0.183 ^{b} ±0.023	1.341 ^{b} ±0.122	1.859 ^{c} ±0.095	1.342 ^{b} ±0.132	0.914 ^{a} ±0.065
	T2	0.165 ^{a} ±0.021	0.162 ^{a} ±0.019	0.165 ^{a} ±0.022	0.214 ^{b} ±0.025	1.301 ^{b} ±0.121	1.819 ^{c} ±0.098	1.302 ^{b} ±0.129	0.874 ^{a} ±0.062

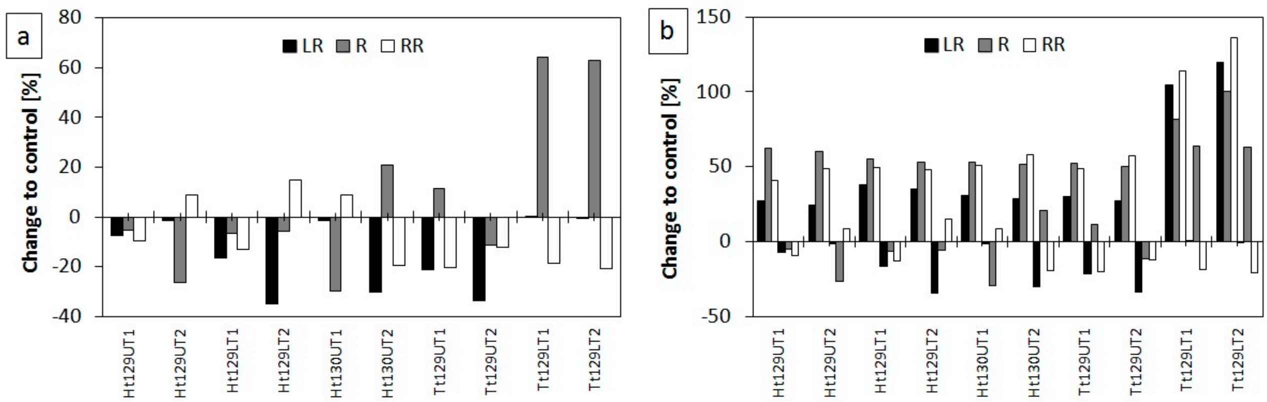


Figure 4. Changes in the values of (**a**) moisture content *MC* and (**b**) dry bulk density *BD* in relation to control.

On the horse trail Ht129, the dry bulk density of soil did not exceed 1.123 g·cm^{-3} (Table 3). However, after skidding, a clear increase was noted in bulk density over the entire trail width in the lower (L) section (LR, R, RR) (4.3% on average), while an increase was observed in density on the right side of the trail in the upper section (2.8%). This is due to the shape of the trail, which had a steep slope and was straight in its lower part, but curved in the upper section. In this case, the right side of the upper part of the trail (the outlier) was on the inside of the more heavily loaded side of the curve (horse movement and some dragging of the load). The bulk density of soil was significantly higher on the tractor trail Tt129 (mean 1.411 g·cm^{-3}) compared to both horse skid trails (mean 0.968 g·cm^{-3}). In the middle part of the tractor trail in its lower section, the mean bulk density of both terms reached 1.839 g·cm^{-3}. Irrespective of the measurement location, a slight decrease in bulk density was found on the tractor trail after skidding (from 1.8% to 2.7%), which may be related to the movement of the tractor as well as the soil shearing and mixing by the machine wheels. Tractor movement at such a high bulk density at time T1 (mean for the trail 1.427 g·cm^{-3}) did not cause significant changes at time T2 (mean for the trail 1.395 g·cm^{-3}), whereas in relation to the control the increase recorded in bulk density on the horse trail was 57.6% (Ht130UT2) and on the tractor trail was 119% (Tt129LT2) (Figure 4b).

3.2. Soil Compactness

On both horse trails (Ht129, Ht130), soil compactness (Table 4) assumed the highest values in the middle of the trail (R) where the load moved, and reached 6.87 MPa in the layer up to 10 cm, 10.03 MPa up to 20 cm, and 7.56 MPa up to 30 cm. In the upper sections of these trails, significantly higher values of compactness were found on the right side (RR). As observed in the case of bulk density, this result is related to the route of the trail in the terrain and a stronger load on this part of the trail by a working horse and partly by the dragged load. The increase in compactness recorded for the horse trails in relation to the control (Figure 5) was 238% in the center of the trail (R) at depths ranging from 11 to 20 cm. Soil compactness on the tractor trail was more similar across the entire track width, due to the characteristics of the skidding vehicle (interaction with the greater width of the machine wheels and the trailed load). The value of soil compactness in the layer up to 10 cm was 7.92 MPa, up to 20 cm was 8.48 MPa, and up to 30 cm was 6.49 MPa. The compactness values determined on the tractor trail were generally more similar in the soil profile, which is due to constant high loads falling on the ground (tractor and load weight) related to the intensity of use (number of passes). This may indicate the accumulation of compaction along the entire width of the trail and at greater depths. The increase in compactness observed on the tractor trail in relation to the control (Figure 5) was 260% in the center of the trail (R) at depths ranging from 21 to 30 cm.

Table 4. Mean (±SD) soil compactness in trails and control plots (superscript a–d: homogeneous groups determined by Tukey's test, $p < 0.05$).

Trail	Date	Penetration Resistance *PR* [MPa]											
		Depth p1: 0.0–10.0 cm				Depth p2: 10.1–20.0 cm				Depth p3: 20.1–30.0 cm			
		LR	R	RR	Contr	LR	R	RR	Contr	LR	R	RR	Contr
Ht129U	T1	2.42 ^{a} ±1.68	4.24 ^{b} ±2.01	4.94 ^{b} ±1.26	2.24 ^{a} ±1.05	1.74 ^{a} ±0.76	2.81 ^{ab} ±0.86	3.80 ^{b} ±2.55	1.74 ^{a} ±1.49	2.72 ^{a} ±0.68	4.48 ^{b} ±1.35	2.74 ^{a} ±2.20	3.13 ^{a} ±1.88
	T2	2.16 ^{a} ±0.99	5.83 ^{b} ±4.66	5.30 ^{b} ±1.54	2.12 ^{a} ±0.62	1.62 ^{a} ±0.92	2.75 ^{b} ±0.85	3.03 ^{b} ±1.12	1.55 ^{a} ±0.95	2.67 ^{a} ±0.88	4.44 ^{b} ±1.31	2.25 ^{a} ±0.62	3.09 ^{a} ±1.64
Ht129L	T1	2.50 ^{ab} ±0.66	3.07 ^{a} ±2.13	3.48 ^{a} ±1.85	2.06 ^{ab} ±0.73	2.13 ^{a} ±0.95	4.74 ^{b} ±1.18	4.77 ^{b} ±2.17	1.62 ^{a} ±0.89	1.35 ^{a} ±0.68	3.20 ^{a} ±2.33	2.84 ^{a} ±2.20	2.74 ^{a} ±0.97
	T2	2.48 ^{ab} ±0.62	2.86 ^{a} ±1.64	3.19 ^{a} ±1.00	1.92 ^{b} ±0.64	2.28 ^{a} ±1.24	5.00 ^{b} ±1.54	4.86 ^{b} ±2.36	1.66 ^{a} ±0.92	1.19 ^{a} ±0.66	2.79 ^{b} ±0.90	2.23 ^{b} ±0.49	2.73 ^{b} ±0.92
Ht130U	T1	2.24 ^{a} ±0.96	6.87 ^{b} ±3.26	4.44 ^{a} ±4.07	2.21 ^{a} ±1.01	1.62 ^{a} ±0.98	7.39 ^{b} ±2.00	1.49 ^{a} ±0.26	1.74 ^{a} ±1.49	2.40 ^{a} ±0.78	5.60 ^{b} ±2.69	7.56 ^{c} ±5.12	3.09 ^{a} ±1.58
	T2	2.29 ^{a} ±1.40	7.40 ^{b} ±3.91	3.68 ^{a} ±1.26	2.47 ^{a} ±2.01	1.82 ^{a} ±1.12	7.30 ^{b} ±1.99	1.84 ^{a} ±0.69	1.32 ^{a} ±0.45	2.65 ^{a} ±0.19	5.37 ^{a} ±2.72	7.85 ^{b} ±4.57	3.09 ^{a} ±1.58
Ht130L	T1	2.09 ^{a} ±0.48	3.54 ^{a} ±1.72	4.71 ^{b} ±3.61	2.02 ^{a} ±0.56	3.38 ^{a} ±2.01	7.20 ^{b} ±5.36	8.84 ^{b} ±3.98	2.91 ^{a} ±0.91	1.59 ^{a} ±0.38	5.50 ^{b} ±6.10	4.95 ^{a} ±3.49	1.30 ^{a} ±0.32
	T2	2.12 ^{a} ±0.46	3.72 ^{bc} ±2.42	5.18 ^{c} ±3.59	2.52 ^{ab} ±1.32	2.92 ^{a} ±1.01	8.54 ^{b} ±5.32	8.54 ^{c} ±3.81	3.05 ^{a} ±1.12	1.69 ^{a} ±0.38	5.55 ^{b} ±6.00	5.22 ^{a} ±3.70	1.36 ^{a} ±0.70
Tt129U	T1	3.42 ^{a} ±1.04	7.92 ^{b} ±2.66	3.57 ^{a} ±1.12	2.12 ^{a} ±1.05	4.31 ^{a} ±0.88	8.29 ^{b} ±2.43	6.38 ^{b} ±1.99	1.97 ^{a} ±1.49	3.74 ^{a} ±1.32	5.66 ^{a} ±0.86	6.49 ^{b} ±4.83	4.08 ^{a} ±2.14
	T2	3.92 ^{a} ±1.17	7.63 ^{b} ±2.72	3.59 ^{a} ±1.12	2.15 ^{a} ±1.1	4.51 ^{a} ±0.88	8.48 ^{c} ±2.22	6.09 ^{b} ±1.99	2.42 ^{a} ±1.73	3.54 ^{a} ±1.39	6.10 ^{b} ±0.86	6.59 ^{b} ±4.83	4.02 ^{a} ±1.98
Tt129L	T1	4.23 ^{a} ±2.22	6.18 ^{a} ±1.95	4.71 ^{a} ±2.04	2.42 ^{b} ±3.55	5.85 ^{a} ±1.87	6.34 ^{b} ±1.97	5.35 ^{ab} ±2.16	1.75 ^{c} ±0.47	4.08 ^{a} ±1.66	4.89 ^{a} ±1.56	5.05 ^{a} ±1.79	5.67 ^{b} ±3.21
	T2	3.83 ^{ab} ±2.13	6.26 ^{b} ±2.04	4.83 ^{ab} ±2.05	2.51 ^{a} ±4.32	4.51 ^{a} ±1.85	6.43 ^{ab} ±2.05	5.49 ^{b} ±2.15	1.78 ^{c} ±0.39	4.18 ^{a} ±1.66	4.75 ^{a} ±1.56	4.90 ^{a} ±2.01	5.82 ^{b} ±3.4

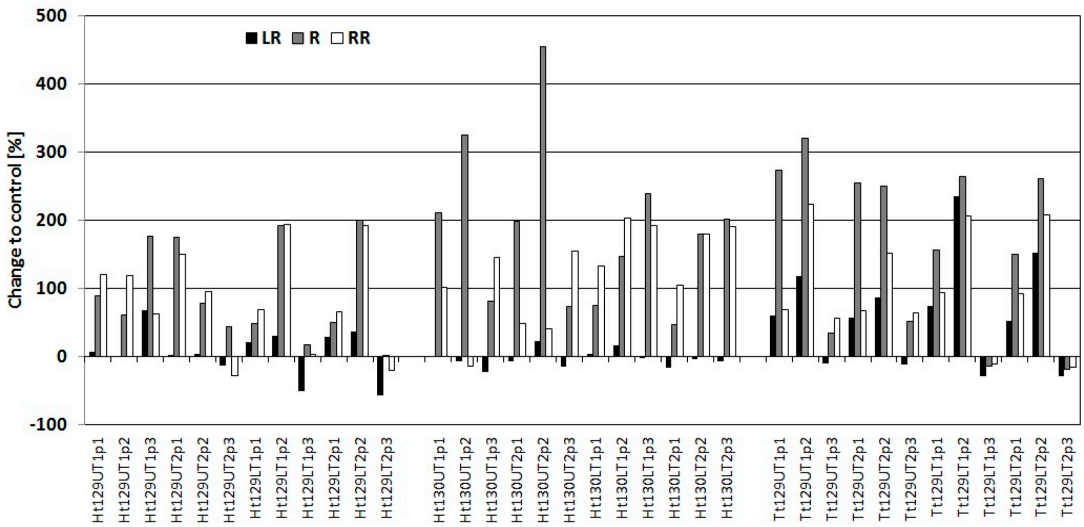


Figure 5. Increase in soil compactness *PR* on trails relative to control recorded for depths p1 (0.0–10 cm), p2 (10.1–20 cm), and p3 (20.1–30 cm).

3.3. Surface Relief of Skid Trails

The terrain profiles of horse and tractor trails clearly showed differences (Figures 6–8), due to the specific nature of the skidding means. These differences were associated with the following: width of the trails (tractor wheel and horse leg spacing); impact on the soil (point-like hooves in the case of horse and belt-like wheels in the case of tractor); size of the load (different unit weights of the load); and specificity of the load (single pieces skidded by horse and many pieces skidded by tractor). The asymmetry of the horse trails due to their course in the terrain (combination of the slope of the terrain and the course of the trail in relation to the contour lines) was clearly evident (Figures 6 and 7).

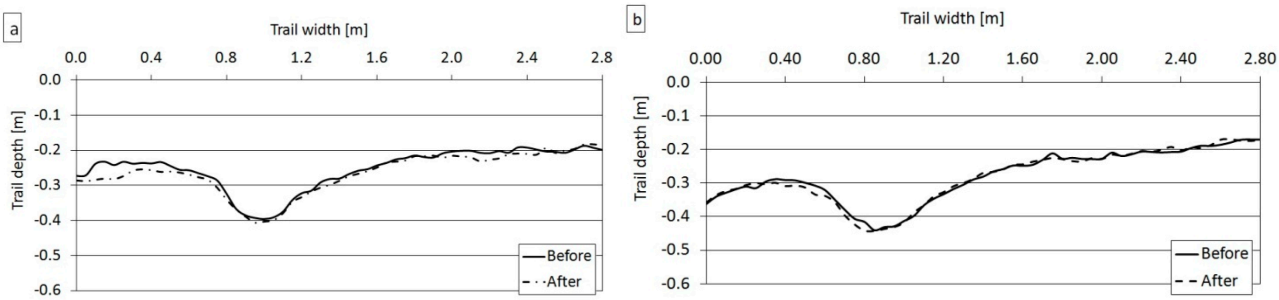


Figure 6. Topography on the trail sections before and after skidding: (**a**) Ht129U and (**b**) Ht129L.

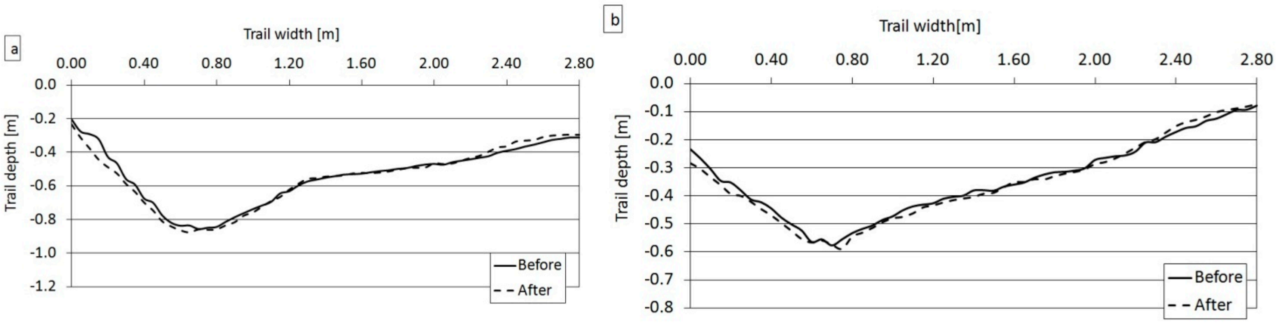


Figure 7. Topography on the trail sections before and after skidding: (**a**) Ht130U and (**b**) Ht130L.

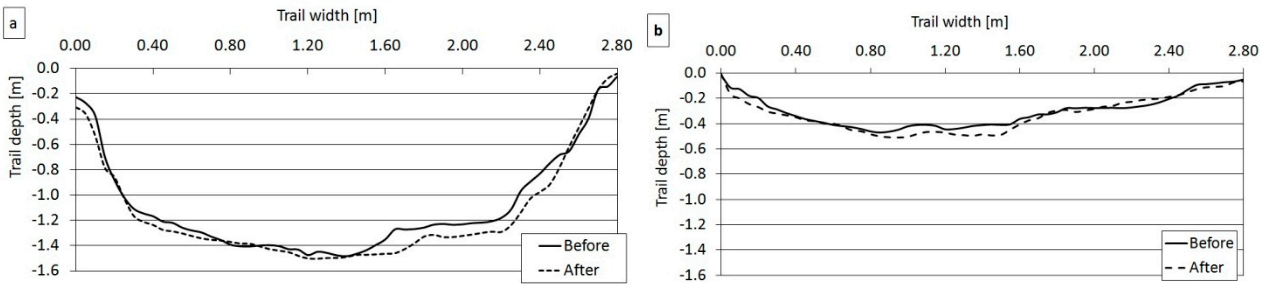


Figure 8. Topography on the trail sections before and after skidding: (**a**) Tt129U and (**b**) Tt129L.

The tractor trail (Figure 8), especially in the upper section, was symmetrical due to its straight course descending the hill. All trails showed a change in profile due to skidding (T1 vs T2), as well as in the average and maximum slope which was particularly visible for Tt129U (Table 5).

Table 5. Average and maximum ground slope in the central 1.5-m-wide section of the trail before (T1) and after timber skidding (T2).

Measurement Variant	Average/Maximum Slope Calculated for Profiles I and III (%)					
	Ht129U	**Ht129L**	**Ht130U**	**Ht130L**	**Tt129U**	**Tt129L**
Before skidding	35.3/42.8	29.3/34.2	60.1/68.6	26.4/36.2	11.4/24.8	8.1/17.2
After skidding	40.4/44.6	26.0/31.8	50.3/58.8	26.9/35.2	25.2/39.0	3.1/19.2
Change (%)	14.2/4.2	−11.3/−7.0	−16.3/−14.3	1.8/−2.8	−121.2/57.3	−61.4/11.6

The maximum rut depths relative to the surface next to the trail (Table 6) varied widely. Before skidding, the maximum rut depth was 1.462 m on tractor trail Tt129, 0.281 m on horse trail Ht129, and 0.679 m on horse trail Ht130. Increases noted in depth after skidding were highest for the tractor trail Tt129L (10.8%) and lowest for the horse trail. For Tt129L, a decrease was observed in rut depth after skidding, which may have been due to the application of soil to the trail during load dragging.

Table 6. Average and maximum depth in the central 1.5-m-wide section of the trail before (T1) and after timber skidding (T2).

Measurement Variant	Average/Maximum Depth on the Trail Calculated for Profiles I, II, and III (cm)					
	Ht129U	**Ht129L**	**Ht130U**	**Ht130L**	**Tt129U**	**Tt129L**
Before skidding	10.5/22.4	14.4/28.2	41.8/67.9	31.9/49.8	128.5/142.9	36.9/46.0
After skidding	11.4/23.4	14.0/28.1	42.4/68.9	33.4/51.7	134.8/146.2	40.8/51.0
Change (%)	8.7/4.6	−2.5/−0.6	1.4/1.5	4.8/3.9	4.9/2.3	10.5/10.8

Interesting changes were recorded in soil volumes on the cross section of the trails (Figures 9–11). For the horse trails (Ht129 and Ht130), soil loss was evident in the lower parts (L) on the left side where the load was dragged along the trail bed, whereas on the right side the increase in volume was much smaller.

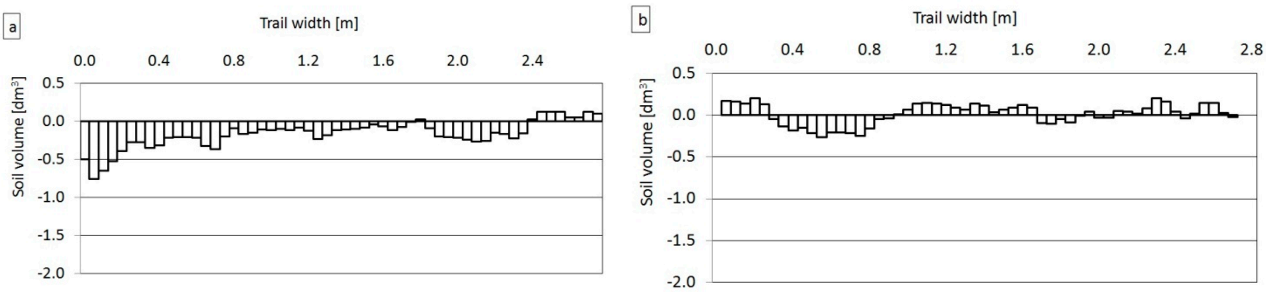


Figure 9. Changes in soil volume on trail sections before and after skidding: (**a**) Ht129U and (**b**) Ht129L.

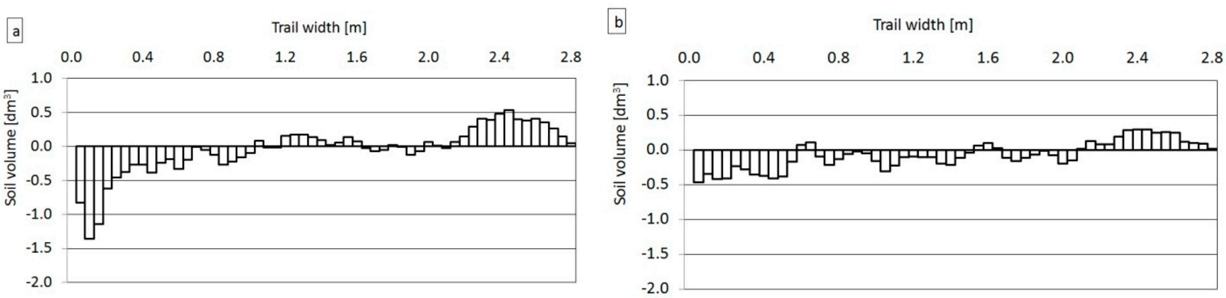


Figure 10. Changes in soil volume on trail sections before and after skidding: (**a**) Ht130U and (**b**) Ht130L.

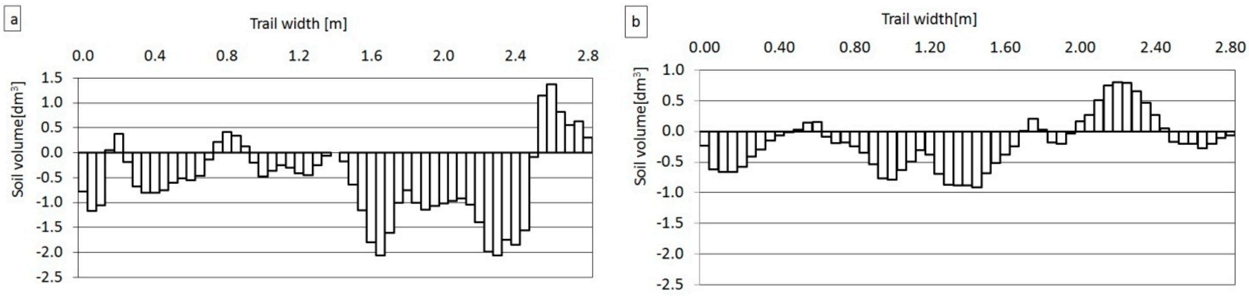


Figure 11. Changes in soil volume on trail sections before and after skidding: (**a**) Tt129U and (**b**) Tt129L.

For tractor trail Tt129, a pronounced soil loss was noted in the upper (U) and lower (L) parts of the trail, especially in the longitudinal axis (R). Soil loss from trails in their deepest areas may also have been influenced by surface runoff. According to meteorological data, the period between the measurement dates (T1—29 July 2015 and T2—22 October 2015) was marked by quite heavy rainfall reaching up to 160 mm. The highest total loss of soil from a 10-m long trail (Table 7) was observed in the upper part of the tractor trail Tt129U, amounting to nearly 1.563 m^3, while in the lower part of the trail the loss was 0.675 m^3 (Tt129L). Significantly lower values of soil loss were recorded on horse trails, ranging from 0.129 to 0.418 m^3. For horse trail Ht129U, nearly 15 times more soil was lost compared to the soil deposited due to skidding and other factors between the measurements. The total soil erosion, which was calculated as the difference between soil taken away and soil deposited per 10 m of the trail (Table 7), was found to be the highest on the tractor trail in the upper part (Tt129U), reaching 1.314 m^3. A high value of 0.434 m^3 was also recorded for the lower part of this trail (Tt129L). For the horse trail Ht129, the erosion was at a relatively high level (0.390 m^3) even in the upper part (U).

Table 7. Volume of soil applied, moved, and stripped from the trail after skidding.

Soil Kind	Soil Volume (m^3) for 10-m Trail Length					
	Ht129U	Ht129L	Ht130U	Ht130L	Tt129U	Tt129L
(lo)	0.418	0.129	0.394	0.312	1.563	0.675
(ap)	0.028	0.158	0.274	0.119	0.249	0.241
(lo) + (ap)	0.446	0.288	0.669	0.431	1.812	0.917
(lo) − (ap)	0.390	−0.029	0.120	0.194	1.314	0.434
(lo)/(ap) *100 (%)	1479.0	81.6	143.8	263.3	626.9	279.7

(ap)—soil applied, (lo)—soil lost.

4. Discussion

The results of the study indicated that necessary logging works carried out in the Gorce National Park do have an impact on the environment, which confirms the statements published by Wałdykowski [12]. Measurements made in two dates, with an interval of three months (T1—29 July 2015 and T2—22 October 2015), during which the existing multiyear trails were used quite intensively (198.2 m^3 of timber were felled), indicate changes in soil parameters in the monitored period of time, as well as in the lie of the land on the skid trails. Significant differences were noted in the magnitude of these changes between horse and tractor trails, as indicated by the analyzed soil compactness, moisture content, bulk density, and terrain deformation. These differences were related to the nature of the skidding means used: In easily accessible terrain with a slight incline, skidding of large loads was carried out by a tractor, while in areas with a steep incline where machine operation is problematic, horse skidding was performed. The choice of the skidding means was determined not only by the possibility of using a skidder but also by the need to minimize the environmental load. It is well known that the terrain of the Gorce National Park is susceptible to erosion, which is evidenced by the deeply incised V-shaped valleys, steep slopes, numerous landslides, and a strong network of streams [39], which is associated with the geological structure (flysch formations based on sandstones, conglomerates, and shales of the Magura Nappe) [40,41]. The study area had mainly brown soil with a lot of skeletons [42], and the geological structure of the studied trials and their susceptibility to erosion were reflected by the measurements made. The highest value of average erosion, as expected, was recorded for trail Tt129, where skidding was performed by a tractor. Soil erosion was particularly high in the upper section of this trail, where for a 10-m trail length the eroded soil volume was determined at 1.314 m^3. The use of a heavy tractor and repeated skidding of large loads, combined with the significant slope of the terrain, were the factors causing such high erosion. For the horse trails, the erosion values were lower, although in the upper section of trail Ht129, characterized by a significant slope, erosion occurred at a high level (0.390 m^3 per 10 m). Elsewhere, erosion was relatively low, and even in the lower section of horse trail Ht129, only a small amount of soil carryover was recorded after skidding (0.029 m^3 per 10 m). Obviously, soil gain without loss is detrimental to the ground surface, because it indicates the displacement of soil masses from another section of the trail. The measurements of soil compactness or bulk density indicated significant soil compaction in the case of the tractor trail, which was expected, as a similar effect was reported by other authors [26,43–45]. Such changes can be long-lasting and affect plant growth [23,46–48]. The physical parameters of soil on this constant perennial skidding trail were not changed significantly by skidding, as they were already found to be high prior to skidding performed during the monitored period. In the case of horse trails, an increase was noted in compactness as well as bulk density, especially on the parts of trails with a steep slope and on the side of the trails that was more heavily loaded during the skidding performed (horse passes and loads from the load). Such changes in the soil (compaction) outside the main route of the horse passage were also noted with horseback touring in a recent study [49]. Furthermore, differences were noted in soil moisture along the trails and in the control between the trails that were in different divisions. This may be related to the remoteness of the studied trails from each other, their different locations, and the differences in forest cover, soil, as well as the intensity of rainfall.

5. Conclusions

The results of the study confirmed the negative effect of tractor skidding on soil parameters and the resulting deformation of the land surface. In the case of horse skidding, deformations in a narrow strip of ground and changes in soil parameters were observed, which resulted from smaller loads of skidded timber and a different impact of horse hooves on the soil compared with tractor wheels. Soil compactness was high across the entire width of the tractor trail and equalized at individual levels, and the increase in values on the trail relative to the control was significantly higher compared to the horse trails. During the monitoring period, soil compactness changed only slightly as a result of skidding, because the skid trails, especially the tractor skid trail, were perennial with fixed levels of compactness. The most important factor increasing erosion on skid trails, next to the skidding method (dragging/semi-forwarding), seems to be the means of skidding used (horse/tractor), which causes tearing of the topsoil layer, soil displacement, and soil compaction in ruts, while longitudinal gradients of used skid trails undoubtedly increase erosion. This is particularly true in the case of skid trails that are actually created during work in the field, without any previous preparation, often running perpendicular to contours, where the soil layers disturbed by skidding are washed away by abundant surface runoff during heavy rainfall. It should be emphasized that the logging technologies applied in the study area corresponded both to the recommendations and logic of performing skidding works by different means depending on terrain conditions. The study confirmed that it is reasonable to use a horse for skidding small loads on a large slope, and a tractor for skidding from places where the load is considerable and on a skid trail designed for many years of skidding.

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