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Soil and Residual Stand Disturbances after Harvesting in Close-to-Nature Managed Forests

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Abstract: Close-to-nature forestry is a viable option to manage forests that are resilient to the challenges presented by climate change. The new silvicultural schemes necessitate adapting the operational side, posing challenges to productivity and the environmental effects of harvesting machinery and technologies. This study focused on analysing the disturbance of residual stands and forest soils in stands that were being restructured into multistorey, close-to-nature managed ones using low-impact forest harvesting technologies. Measurements were performed in four stands after logging, divided into 30 sample plots with dimensions of 20 × 20 m. Within the plots, the disturbance of the residual stands and changes to the soil parameters, such as the soil bulk density (g·cm^{-3}) and soil penetration resistance (MPa), were measured. The results showed that the intensity of the residual stand disturbance reached between 13% and 23% and was not significantly ($p > 0.05$) affected by the intensity of the performed harvesting operations. The mean size of the wounds was between 38.99 and 233.05 cm^2, and wounds were most frequently in the size category of 11–50 cm^2. Regarding soil disturbance, Spearman's correlation showed a significant relationship ($p < 0.05$) between the longitudinal slope and soil bulk density in the rut of the trail. The relative increase in BD showed that the largest increase occurred between the stand (undisturbed) and rut locations (12.5% to 24.77%). Penetration resistance measurements were affected by low moisture content and high coarse fragment content. Subsequently, Spearman's correlation did not show ($p > 0.05$) a relationship between the soil bulk density and penetration resistance. Therefore, we can conclude that, from an environmental perspective, the proposed technologies are viable options for foresters who manage close-to-nature forests, and there was less disturbance of residual stands and forest soil caused by harvesting machinery.

Keywords: penetration resistance; bulk density; residual stand disturbance; close-to-nature forest management; cut-to-length logging

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1. Introduction

Timber harvesting represents a key factor in the ecological management of stands, changing the stand structure and species diversity [1]. Management strategies are increasingly focused on the diversification of vertical and horizontal forest structures, including a greater diversity of tree species. The main goal of selection cutting management is to provide mixed and uneven-aged stands that are close to nature [2]. The importance of the concepts of close-to-nature or continuous-cover forestry is widely accepted [3]. The general principles and development history of 'close-to-nature silviculture' are known to many managers of woods and forests [4]. Close-to-nature management is a promising forestry management approach, which simultaneously integrates wood production and the ecological service functions of a forest at a relatively small spatial scale, such as the stand level, by developing a structure similar to that of an original forest [5,6]. Since 1989, the Pro

Silva organisation has been one of the strongest proponents of the alternative 'natural' or 'close-to-nature' approaches in Central Europe [7,8]. In these forest management systems, the specific species mixtures and irregular age structures are promoted as a response to even-aged plantations, which have become prevalent in some parts of Central Europe. These even-aged, uniform, monoculture plantations are viewed as more susceptible to disturbances and 'far-from-nature' [9,10]. Forest harvesting in such management systems is based on meticulously following the least-damaging felling direction and cut-to-length harvesting. For extraction, the machinery uses a dense road and trail network while trying to minimise disturbances to soils and standing trees [11].

Soil compaction and displacement are important consequences of forest operations [12,13]. The disturbance of the soil surface, changes in physical, chemical, and biological properties, and damage to natural regeneration and to the residual stand are the main impacts of logging operations and wood extraction on soil and forest stands [14]. Soil is a critical element for sustainable forest management and is a relatively slowly renewable natural resource [15], but sustainable forest management and the appropriate application of logging activities could guarantee good soil resilience [16,17]. The extent and severity of soil disturbances during harvesting operations depend on several factors that can be divided into three groups: (i) stand conditions, (ii) yarding logistics, (iii) forest road network characteristics [18]. Besides the negative effects of the machinery on the forest soil, the damage to the residual stand is also important to consider. Sirén et al. [19] define residual stand damage as bark and cambium removal, potentially including partial wood tissue disturbance. In extreme cases, it can also include tree breakage. According to Picchio et al. [18], the level of damage to the residual stand sustained during forest operations depends on many factors. For single-tree selection cutting, damage to residual trees is considered one of the most important operational challenges in forest harvesting [20], as it endangers the goal of the management system by decreasing growth, increasing the incidence of decaying wood, and inducing a higher probability of mortality for severely damaged trees [21]. Due to the use of technologies and logging interventions specific to close-to-nature forest management, a lower extent of post-harvest disturbance is to be expected compared to conventional technologies deployed in primarily deciduous stands. Prior studies that dealt with post-harvest soil and residual stand disturbance when close-to-nature forest management was used were conducted in stands that exhibited higher vertical differentiation, thus enabling the use of larger machinery and other technologies [14,19,22–24].

The main aim of this study was to analyse the effects of low-impact forest operations on the soil and residual trees in forest stands that are managed in a close-to-nature, multistorey system with primarily deciduous species. The scenarios studied in this paper are not well researched, despite the expected increase in the use of such harvesting systems in the future.

The following hypotheses were tested: (i) the residual stand disturbance in close-to-nature managed forest stands is lower than in intensively managed forest stands; (ii) soil disturbance in close-to-nature managed forest stands is lower than in stands managed in other systems.

2. Material and Methods

Measurements were carried out in Stará Myjava municipal forests, which manages 1067 ha of forests. Forests covering 449 ha were selected for restructuring into close-to-nature, multistorey stands. The annual volume of harvested timber is 9200 m^3 and depends on the share of salvage logging. The forest road network spans 17.3 km, with a density of 15.9 m/ha, and 27 km of technological trails, with a density of 25 m/ha. The mean annual temperature ranged between 6 and 7 °C, and the mean annual precipitation between 2015 and 2022 ranged between 373.6 and 691.6 mm. The most abundant soil types in the area are Eutric Cambisols [25]. Regarding the soil texture, the soils are loams to sandy loams with a share of fine particles (<0.01 mm) ranging from 30% to 60%. The area is located in the flysch zone of the West Carpathians formed by alternating layers of claystones and sandstones of the Mesozoic and Tertiary age. The Flysch Belt is an allochthonous nappe system that thrusted during the Paleocene and Miocene tectogenesis over the West European plate [26].

Prior to the research, four forest stands were selected (Table 1), with a majority share of deciduous tree species in the mix, aged between 45 and 70 years, and DBH (diameter at breast height) in the range between 18 and 34 cm. The stands were selected for permanent restructuring into multistorey stands with the application of close-to-nature management principles. The interventions carried out were selection thinning, which is intended to remove unstable trees on a regular basis, thus enabling natural regeneration and a differentiated vertical structure of the residual stand. The intervention intensity differed in particular sections of the forest stands.

Table 1. Basic information related to the observed forest stands.

Stand	**51a**	**10**	**9b**	**59**
Elevation a.s.l. (m)	460–530	380–440	380–430	410–460
Area (ha)	11.37	15.49	13.35	7.85
Age (years)	45	60	70	60
Slope (%)	30	30	30	30
Forwarding distance (m)	200	200	150	600
Density (-)	0.9	0.9	0.9	0.9
Species composition (%) [(a)]	Fs 85; Pa 10; Ld 5	Fs 85; Qp 5; Ld 5; Pa 5	Fs 55; Qp 15; Cb 10; Fe 5; Ld 5; Pa 5; Pm 5	Fs 85; Ld 12; Pa 3
Mean stem volume (m^3)	0.17	0.70	0.83	1.09
Mean height (m)	17	25	26	29
DBH (cm)	18	29	30	34
Intervention	Select. thinning	Select. thinning	Select. thinning	Select. thinning
Harvesting volume (m^3)	216.96	375.9	367.43	377.09
Harvesting area (ha)	2.0	2.70	3.0	7.85
Soil type (WRB 2015)	Cambisol	Cambisol	Cambisol	Cambisol
Harvesting month	II.–IV.	VII.–IX.	V.–IX.	IV.–V.
Logging methods	Cut-to-length	Cut-to-length	Cut-to-length	Cut-to-length
Felling technology	Chainsaw	Chainsaw	Chainsaw	Chainsaw
Removal machine [(b)]	MK 18	KAPSEN 18	Landini Vision 100	MK 18
Extraction machine [(c)]	Fortera + AGA LV 10	LKT + VKS	LKT + VKS	Fortera + AGA LV 10
Cost of Felling + Removal technology (EUR/m^3)	19.50	17.50	17.50	19.50
Cost of extraction (EUR/m^3)	7.50	8.33	8.33	7.50
Cost$\sum$ EUR/m^3	27	25.83	25.83	27
Number of sample plots	7	7	7	9

Species composition [(a)]: Fs—Fagus sylvatica; Qp—Quercus petraea; Cb—Carpinus betulus; Fe—Fraxinus excelsior; Ld—Larix decidua; Pa—Picea abies; Pm—Pseudotsuga menziesi; Ps—Pinus sylvestris; removal machine [(b)]—machines used to move the timber from the stump to the edge of the trail; extraction machine [(c)]—machines used to move the timber from the edges of the trails to the roadside landing.

The harvesting technology in all forest stands was cut-to-length and consisted of chainsaw felling, limbing, and bucking into 4–6 m logs. The logs were subsequently removed to the edges of the technological trails by a tracked mobile winch or a skidder-mounted winch. From the edges of the trails, the logs were forwarded to roadside landings or directly to customers by forwarders. Detailed information on the machinery used is available in Table 2.

Table 2. Basic technical parameters of the machinery used in the observed forest stands.

	MK 18	**Kapsen 18**	**Landini Vision 100**	**Fortera 140 HSX**	**AGA LV10 ***	**LKT 81T**	**VKS**
Machine type	Tmw [(a)]	Tmw [(a)]	Ft [(b)]	Ft [(b)]	Ftwc [(c)]	S [(d)]	Ftwc [(c)]
Cylinders/displacement (cm^3)	2/624	2/570	4/4400	4/4200	-	4/4562	-
Performance (kW)	13.42	13.43	69.0	101.4	-	74.5	-
Fuel type	petrol	petrol	diesel	diesel	-	diesel	-
Mass (kg)	900	1100	3329	4760	4600	7065	3600
Number of axles	-	-	2	2	2	2	2
Tyre type	-	-	Mitas	Mitas/GTK	Alliance	Mitas	Pneumant
Front tyres	-	-	440/65 R24	480/65 R24	500/45–22.5	16.9–30	16–20
Rear tyres	-	-	540/65 R34	600/65 R38	500/45–22.5	16.9–30	16–20
Tyre width (cm)	40	40	-	-	-	-	-
Winch (kN)	1 × 13	1 × 16	2 × 55	-	-	2 × 80	-
Operator age (years)	48	21	45	47	-	45	-
Operator experience (years)	2	2	20	22	-	20	-

Tmw [(a)]—tracked mobile winch (iron horse); Ft [(b)]—farm tractor; Ftwc [(c)]—forestry trailer with crane; S [(d)]—skidder; * forestry trailer with crane equipped with hydraulic wheel drive.

Before the harvesting operations, the forest stands were prepared by marking the stand division by primary technological trails (40 m apart), which were directed downhill, and secondary trails (20 m apart), which were directed along the contour. The width of the trails was 4 m. Trees intended for felling were marked by reflective colour at breast height and at the foot of the trees. The machine operators were sufficiently experienced in operating the machinery and were informed about the logging technology and natural conditions in the forest stands.

The damage to the residual stands and forest soil was observed on 30 sample plots, each with an area of 20 × 20 m, which were established in stands after logging. The plots were placed uniformly to contain the secondary trails. In general, the area of the sample plots covered 10% of the total area of the stand in stands up to 50 000 m^2. In stands larger than 50,000 m^2, the area of the sample plots was 5% of the total area of the stand [27]. However, the number of sample plots in each forest stand depended on the harvesting area rather than the total area of the stand.

2.1. Residual Stand Disturbance

On each sample plot, the following parameters were recorded: (i) slope (longitudinal and transversal); (ii) number of residual trees; (iii) number of stumps; (iv) number of damaged trees, according to tree species; (v) number of injuries per tree. For each damaged tree, the following were observed, according to [28]: (i) distance of the tree from the trail: (a) 0–2 m, (b) 2.1–4 m, (c) 4.1–6 m, (d) 6.1–8 m, (e) 8.1–10 m; (ii) wound location: (a) root wound (aboveground) at a distance of 0.21 to 1.0 m from the foot of the tree, (b) wound of the butt part of the stem at a maximum distance of 0.2 m from the stem and to a height of 0.3 m on the stem, (c) stem wound at a height between 0.3 and 1.0 m, (d) wound at a height above 1 m. All wounds were rated according to five levels of wound severity: (iii) wound size: (a) <10 cm^2 (negligible), (b) 11–50 cm^2 (very small), (c) 51–100 cm^2 (small), (d) 101–200 cm^2 (medium), (e) 201–300 cm^2 (large), >300 cm^2 (very large), (f) root rupture or destructive breakage; (iv) wound severity: (a) the top layer of bark damaged, (b) bark crushed, (c) wood exposed but undamaged, (d) wood exposed and slightly damaged, (e) wood exposed and heavily damaged.

From the measured data, the following parameters were calculated: (i) intensity of the injury, II (%) (Equation (1)); (ii) intensity of harvesting, IH (%) (Equation (2)).

$$\text{II\%} = \left(\frac{\text{Number of trees injured}}{\text{Number of trees injured} + \text{Number of trees uninjured}}\right) \times 100 \quad (1)$$

$$\text{IH\%} = \left(\frac{\text{Number of stumps}}{\text{Number of stumps} + \text{Number of remaining trees}}\right) \times 100 \quad (2)$$

2.2. Soil Disturbance

To observe the differences in soil parameters on the technological trails after harvesting, measurement points were placed on the opposite sides of each plot where the trails crossed the plots. Within the measurement points, soil parameters were measured at the undisturbed stand (S) (control measured), rut (R), and centre (in between the ruts) (C) locations. This allowed the collection of two sets of material on a single sample plot and a total of six samples. At the aforementioned measurement locations, the soil bulk density (BD) was sampled into Eijkelkamp soil sampling ring kits from the top of the soil (0–10 cm). The kits consisted of cylinders with a volume of 100 cm^3 and the following dimensions: Ø 53 × 50 mm diameter, 51 mm height. The cylinders were inserted into the soil in a cylinder holder. After sampling, the cylinders were sealed with plastic caps, numbered, and shipped to the laboratory for analyses. In the lab, the samples were weighed with an accuracy of 0.01 g, dried for 24 h at 105 °C, and weighed again to determine the dry bulk density, BD (g cm^{-3}). The fresh and oven-dried weights of the samples also served to determine (iii) the soil moisture content, MC (%) (Equation (3)):

$$\text{MC\%} = \left(\frac{\text{fresh sample (g)} - \text{dried sample (g)}}{\text{dried sample (g)}}\right) \times 100 \quad (3)$$

Parallel to soil sampling, the penetration resistance of the soil, PR (MPa), and penetration depth, PD (cm), were tested and recorded in the same S, R, and C system of locations as the bulk density sampling. The penetration resistance parameters were measured with an Eijkelkamp Penetrologger penetrometer (Royal Eijkelkamp, Giesbeek, The Netherlands). For our measurements, we used an 80 cm extending rod and a 30° cone with a 1 cm^2 surface area. The penetration speed was 2 cm s^{-2}. PD (cm) was recorded automatically along with the penetration resistance (MPa) data. The penetration data were stored in the logger unit and subsequently exported using the PenetroViewer program [29].

Soil sampling and PR measurements were performed by the same researcher to ensure a unified measurement procedure. In total, 180 soil samples were collected, and 180 PR measurements were performed.

2.3. Statistical Analyses

To analyse the data, we used MS Excel, Statistica 12.0, and PenetroViewer version 5.08. To verify the II (%), IH (%), BD (g·cm^{-3}), MC (%), PR (MPa), and PD (cm) data distributions, a Shapiro–Wilk test was used, and to verify the homogeneity of the variances, Levene's test was used. Spearman's correlation analyses were used to observe the relationships between the intensity of harvesting and the intensity of injuries to remaining trees, the intensity of injuries to remaining trees and tree density, the intensity of harvesting and average wound size, the BD and MC, and the BD and PR. Kruskal–Wallis ANOVA was used to compare the differences between the intensity of harvesting, intensity of injuries to remaining trees, and wound size, as well as to analyse the relationships between the intensity of harvesting and BD and the intensity of harvesting and PR. Multiple comparisons of p values were used to identify pairs of forest stands with significant differences between the same measurement locations in terms of BD, PR, MC, and PD, as well as to identify differences between pairs of measurement locations within a given forest stand for the BD, SM, PR, and PD variables. To observe the associations between the wound size and distance from the edge of the trail and between wound location on the stems and the wound size and to observe the differences in the frequency of different wound sizes, the frequency of wounds based on the distance from the edge of the trail, and the frequency of wounds based on location on stem, we used a χ^2 test.

3. Results

The results of the Shapiro–Wilk and Levene's tests showed that the majority of data were not normally distributed and their variances were not homogeneous (Table S1). Based on these outcomes, we opted to use non-parametric tests.

3.1. Disturbance of Residual Stands

The mean intensity of harvesting in the stands varied between 119% and 26.8%, with a related intensity of injuries to the remaining trees ranging between 13.1% and 23.4% (Table 3). Spearman's correlation analysis did not show a statistically significant relationship between the two variables ($p > 0.05$). Similarly, Kruskal–Wallis tests did not prove that the differences in the intensity of harvesting (H = 4.50, $p = 0.21$) or the intensity of injuries to the remaining trees (H = 5.65, $p = 0.13$) between stands were significant. Spearman's correlation analysis showed no significant correlation between the intensity of injuries to the remaining trees and the tree density ($p > 0.05$). Most trees (57.1% to 90%) had only one wound, with the size ranging from very small (38.9 cm^2 in stand 51a) to small (89 cm^2 in stand 10 and 96.4 cm^2 in stand 59). In these stands, tracked mobile winches removed timber to the edges of the technological trails. In contrast, the largest wounds were recorded in stand 9b (233 cm^2), where a Landini Vision 100 tractor was used to remove timber by winching. Indeed, a χ^2 test confirmed ($p < 0.01$) that the frequency of injuries in particular wound sizes was significantly different in all observed forest stands. Although the smaller tracked mobile winches caused smaller wounds, the frequency of injuries in stands trafficked by these machines was greater. The differences between average wound sizes between stands were not statistically significant, according to Kruskal–Wallis ANOVA (H = 3.08, $p = 0.38$). On the other hand, we observed a significant relationship between the intensity of harvesting and the average wound size ($\rho = 0.48$; $p < 0.05$). In all forest stands, the most frequent (37.6%–57.6%) wounds were in the 11–50 cm^2 size category.

Most wounds were bark damages, i.e., relatively low-severity categories. The greatest number of injured trees were located up to 2 m away from the technological trails (32%–57.7%), caused by the removal and bunching of timber at the edges of the trails. No association between the wound size and distance from the technological trails was confirmed by the χ^2 test (χ^2 of 30.56 < 31.4; df = 20; $p = 0.06$). On the other hand, there were significant ($p < 0.01$) differences between the number of wounds categorised according to distance to the edge of the trail, excluding stand 59 ($p = 0.09$). In stand 59, the intensity of harvesting was higher, and as a result, the distribution of injured trees was more uniform between intervals of distances to the edge of the trail. The majority of wounds, from the view of location on the stems, were located on the buttresses (41.7%–67.1%), with the exception of stand 10, where wounds were mostly located on the roots (52.8%). A relatively large share of wounds were located on the stems, 0.3 to 1 m high (20.8% to 27.1%). The χ^2 test confirmed that the differences between the stem damage locations were significant in all stands ($p < 0.01$), besides stand 9b, where, due to the larger machinery being used, numerous wounds were found higher up the stems. The χ^2 test results did not confirm an association between the location of the wound on the stems and the distance to the edge of the trail (χ^2 of 13.36 < 21.0; df = 12; $p = 0.34$); however, the size of the wound and its location on the stem were associated (χ^2 of 50.72 > 31.4; df = 20; $p < 0.01$).

Table 3. Disturbance to residual stands caused by the harvesting process.

Stand	**51a**	**10**	**9b**	**59**
Number of trees per hectare	1211	639	640	822
Intensity of harvesting (%)	18.98	23.90	23.08	26.75
Intensity of injuries to trees (%)	13.10	20.21	15.28	23.36
Total number of injured trees	35	27	20	49
Number of trees with 1 wound (n/%)	20/57.14	18/69.23	18/90	30/60
Number of trees with 2 wounds (n/%)	8/22.86	7/26.92	1/5	18/36
Number of trees with 3+ wounds (n/%)	7/20	1/3.85	1/5	2/4
Mean size of the wound (cm^2)	38.99	89.04	233.05	96.37
Total surface area of wounds (cm^2)	2346	4053	1631	6758
Surface area of wounds per hectare (cm^2/ha)	8379	14,475	5826	18,772
	Surface of wounds (cm^2) in size categories (n/%)			
<10	11/18.65	0	2/8.33	3/4.29
11–50	34/57.63	17/47.22	9/37.5	36/51.43
51–100	7/11.86	6/16.67	8/33.34	12/17.14
101–200	7/11.86	7/19.44	3/12.5	10/14.29
201–300	0	2/5.56	0	4/5.71
300>	0	4/11.11	2/8.33	5/7.14
χ^2 ↨ surface area (cm^2)	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$
	Distance of the injured tree from the edge of the trail (n/%)			
0–2 m	14/40	15/57.68	9/42.86	16/32
2.1–4 m	3/8.57	4/15.39	2/9.51	6/12
4.1–6 m	10/28.57	5/19.23	4/19.05	7/14
6.1–8 m	5/14.29	1/3.85	3/14.29	9/18
8.1–10 m	3/8.57	1/3.85	3/14.29	12/24
χ^2 ↨ distance (m)	$p < 0.01$	$p < 0.01$	$p = 0.03$	$p = 0.09$
	Location of wound on the stems (n/%)			
Root damage	9/15.25	19/52.78	7/29.16	7/10
Buttress	34/57.63	9/25	10/41.67	47/67.14
Stem damage (0.3–1 m)	16/27.12	8/22.22	5/20.84	15/21.43
Stem damage (above 1 m)	0	0	2/8.33	1/1.43
χ^2 ↨ location	$p < 0.01$	$p < 0.01$	$p = 0.13$	$p < 0.01$

↨—differences between groups.

3.2. Bulk Density

The smallest BDs (1.04 to 1.21 g cm^{-3}) were recorded at the control S locations, where the soil was undisturbed by machine traffic (Table 4). The largest BDs (1.30 to 1.40 g cm^{-3}) were recorded in the ruts of the skid trails, apart from stand 51a, where the largest BD (1.21 g cm^{-3}) was recorded in between the ruts. The relative increase in BD showed that the largest increase occurred between the S and R locations (12.5% to 24.8%) and S and C (6.2% to 23.1%), whereas the differences between the R and C locations were insubstantial.

The comparison of BDs from the same measurement locations in particular forest stands showed significant differences only between stands 51a and 59 (Table S2) in the S ($H = 10.51$, $p = 0.02$) and R ($H = 11.22$, $p = 0.01$) locations. These differences were caused by the different soil properties in the particular stands, as documented by the significance of the differences in the control location (S). Based on this, we can state that, considering the BD, significant differences between the same measurement locations in different stands were not found. Comparing the S, R, and C locations within each stand, on the other hand, showed significant differences ($p < 0.05$), specifically between the R and C locations (Table S3), which were subjected to the effects of the harvesting machinery. Furthermore, Spearman's correlation showed a significant relationship ($\rho = 0.37$; $p < 0.05$) between the slope and bulk density in ruts, though the relationship between the BD and harvesting intensity was insignificant.

Table 4. Mean bulk density (BD) (g cm^{-3}) with standard deviation (SD) and differences in BD between measurement locations (%), as recorded on sample plots.

	S [a]		**R [b]**		**C [c]**	
	Ø BD [d] ± SD [e]	**Δ [f] S ↔ R (%)**	**Ø BD ± SD**	**Δ R ↔ C (%)**	**Ø BD ± SD**	**Δ S ↔ C (%)**
51a	1.04 ± 0.16	+12.5	1.17 ± 0.23	+3.42	1.21 ± 0.19	+23.06
10	1.13 ± 0.16	+15.04	1.30 ± 0.15	−3.08	1.26 ± 0.18	+3.51
9b	1.09 ± 0.12	+24.77	1.36 ± 0.16	−7.35	1.26 ± 0.15	+6.15
59	1.21 ± 0.13	+15.70	1.40 ± 0.14	−8.57	1.28 ± 0.15	+18.63

S [(a)]—stand; R [(b)]—rut; C [(c)]—centre; BD [(d)]—bulk density; SD [(e)]—standard deviation; ± Δ% [(f)]—percent difference between measurement locations.

As Table 5 shows, the highest MC values (16.2%–30.7%) were measured in the R of the trails in all forest stands. The greatest differences in MC were recorded between the locations S and R (15.6%–52.9%) and locations S and C (3.5%–23.1%).

Table 5. Mean moisture content (MC; %) measured in particular forest stands and measurement locations and the comparison of their differences (Δ; %).

	S [a]		**R [b]**		**C [c]**	
	Ø MC [d] ± SD [e]	**Δ [f] S ↔ R (%)**	**Ø MC ± SD**	**Δ R ↔ C (%)**	**Ø MC ± SD**	**Δ S ↔ C (%)**
51a	20.08 ± 4.44	+ 52.89	30.7 ± 14.96	–19.51	24.71 ± 14.91	+23.06
10	13.98 ± 1.95	+ 15.59	16.16 ± 3.08	–10.46	14.47 ± 2.31	+3.51
9b	18.87 ± 3.46	+ 17.49	22.17 ± 4.96	–9.65	20.03 ± 4.84	+6.15
59	15.19 ± 2.38	+ 35.81	20.63 ± 8.17	–12.65	18.02 ± 6.10	+18.63

S [(a)]—stand; R [(b)]—rut; C [(c)]—centre; MC [(d)]—soil moisture; SD [(e)]—standard deviation; Δ% [(f)]—percent difference between measurement locations.

The multiple *p*-value comparisons showed that, similarly to the soil BD, the soil moisture content at the same measurement locations was significantly different between stands 51a and 59 (Table S4) at the S (H = 10.51, p = 0.02) and R (H = 11.22, p = 0.01) locations. Because the differences were found in the control locations, we attribute them to the different soil parameters. Comparing the measurement locations (S, R, and C) within the stands (Table S5) showed significant differences in the MC only in stand 51a in the ruts (H = 10.68, p = 0.00). In the remaining stands, the MC was not significantly different ($p > 0.05$). Similarly, Spearman's correlation did not show a relationship between the BD and MC ($p > 0.05$).

3.3. Penetration Resistance and Penetration Depth

The penetration resistance of soil varied substantially, mainly because the measurements were conducted on flysch in a low-precipitation period. The highest PR values (Table 6) were recorded in ruts in stands 10 (4.37 MPa) and 9b (4.49 MPa). In stand 51a, the highest PR was recorded in between the ruts (4.38 MPa), and in stand 59, the highest value was in the control, undisturbed stand location (3.94 MPa). Percent PR differences were greatest between S and R locations.

In contrast to the previous soil parameters, penetration resistance differences were not significantly different in the S location (H = 3.32, p = 0.34), while in the R location, they indeed were different (H = 139.01, $p < 0.01$), with the exception of the combination of stands 10 and 9b (Table S6). Considering the C location, differences were significant only for stand 59 (H = 107.32, $p < 0.01$). Comparing the S, R, and C locations in each stand (Table S7) showed significant differences, especially between the R and C locations ($p < 0.01$).

Spearman's correlation analysis did not show a significant relationship between the BD and PR ($p > 0.05$).

Table 6. Mean penetration resistance values (MPa), their standard deviations, and their differences (%) between measurement locations in observed stands.

	S [(a)]		R [(b)]		C [(c)]	
	Ø PR [(d)] ± SD [(e)]	Δ [(f)] S ↔ R	Ø PR ± SD	Δ R ↔ C	Ø PR ± SD	Δ S ↔ C
51a	4.19 ± 1.85	−7.64	3.87 ± 1.90	+13.18	4.38 ± 1.59	+4.54
10	3.93 ± 1.81	+11.20	4.37 ± 1.82	−3.43	4.22 ± 1.67	+7.38
9b	4.03 ± 1.63	+11.41	4.49 ± 1.27	−6.01	4.22 ± 1.29	+4.72
59	3.94 ± 1.90	−12.44	3.45 ± 1.44	+2.61	3.54 ± 1.51	−10.15

S [(a)]—stand; R [(b)]—rut; C [(c)]—centre; PR [(d)]—penetration resistance (MPa); SD [(e)]—standard deviation; Δ% [(f)]—percent difference between measurement locations.

Flysch bedrock and a prolonged period of low precipitation resulted in rather shallow penetration depths (PDs), which were deepest in between the ruts of the trails in stand 59 (27.90 cm) and shallowest in the ruts of the trails in stand 10 (12.49 cm) (Table 7).

Table 7. Mean penetration depths (PDs; cm) in particular forest stands and measurement locations and their differences (Δ; %).

	S [(a)]		R [(b)]		C [(c)]	
	Ø PD [(d)] ± SD [(e)]	Δ [(f)] S ↔ R (%)	Ø PD ± SD	Δ R ↔ C (%)	Ø PD ± SD	Δ S ↔ C (%)
51a	14.13 ± 9.31	−6.16	13.26 ± 10.91	−3.62	12.78 ± 9.03	−9.55
10	15.24 ± 11.19	−18.05	12.49 ± 10.57	+59.65	19.94 ± 15.70	+30.84
9b	26.55 ± 19.18	−1.21	26.23 ± 20.88	−13.34	22.73 ± 16.48	−14.39
59	13.18 ± 9.55	+44.39	19.03 ± 17.47	+46.61	27.90 ± 22.90	+111.68

S [(a)]—stand; R [(b)]—rut; C [(c)]—centre; PD [(d)]—penetration depth (cm); SD [(e)]—standard deviation; Δ% [(f)]—percentage difference of the penetration depth for measurement locations.

The differences in PDs between stands (Table S8) were significant in stand 9b in the case of the S location (H = 172.36, $p < 0.01$), where the deepest penetration was achieved (26.55 cm). In the case of the R (H = 139.79, $p < 0.01$) and C (H = 103.7, $p < 0.01$) locations, significant differences were recorded in stands 51a and 59. Comparisons of PDs between the S, R, and C locations (Table S9) within each stand showed nearly significant differences only in the case of stand 51a (H = 5.41, $p = 0.07$). In stand 9b, the differences between the S and C locations were significant, and in the other stands, the differences between all measurement locations were significant.

4. Discussion

4.1. Disturbance of Residual Stands

Tavankar et al. [22] state that in the Caspian forests of Iran, where selective cutting management is practised, residual stand damage ranges between 10.5% and 23.6%, with a mean reaching 16.9%. Jourgholami [30] reported residual stand damage of 16.4% in a stand with a majority of deciduous tree species, where single or group selective cutting and short-log methods were practised. Other authors [23] stated that, in northern Iran, in stands with a majority representation of *Fagus orientalis* that were managed by individual tree selection, 19.7% disturbance to the residual stand was observed when the cut-to-length method and log skidding were used. In a newer study, Nikooy et al. [31] reported disturbance rates between 8.3% and 19.1% with selective thinning and between 5% and 18% when the whole-tree logging method was used. For comparison, in our case, the stands that were undergoing conversion to close-to-nature management resulted in disturbance rates between 13.10% and 23.36% with an intensity of harvesting between 18.98% and

26.75%. Grzywinski et al. [32] reported a mean residual damage to stands of 5.8% in winter and 10.6% in summer in *Alnus glutinosa* stands with a similar age structure (38–40 years), cut-to-length harvesting, an intensity of harvesting of 13.1%, and manual log handling. In their case, manual log handling proved to be beneficial to the residual stand disturbance rate. In another study [28], the researchers reported, for similar intensities of harvesting (14.5%–23.4%), a disturbance rate between 20.5% and 23.4% for cut-to-length logging, 19.4% for stem-only logging using motor-manual felling and skidding, and between 14.47% and 19.86% for a combination of motor-manual felling, horse timber removal, and skidding with a wheeled skidder. Nikooy et al. [31] reported that with the increasing intensity of thinning, the intensity of the residual stand disturbance also increases. Similarly, Tavankar et al. [22] stated that the intensity of the operation significantly affects the intensity of the disturbance. In our case, this relationship was not supported by the statistical analyses. These authors [22] also stated that the tree density significantly affects the intensity of the disturbance of the residual stand, but in our case, this was not confirmed. Other authors [31] further reported that with selective thinning in stands aged between 34 and 36 years, stems mostly sustained singular wounds (78.6%), while the frequency of two and three wounds was 16.2% and 7%, respectively. Furthermore, Jourgholami [30] stated that when the short-log method was used, 47% of damaged trees sustained one wound per stem, 47% sustained one to three wounds, and 6% sustained more than three wounds. Similarly, our results showed that stems with singular wounds were the most abundant (57.1%–90%). Tavankar et al. [22] reported that the sizes of the injuries varied, depending on the position of the wound on the stem. In our case, the χ^2 test confirmed that the wound size and position were associated. Regarding the wound size, [24] stated that the mean wound size in selection cutting ranged between 311 and 330 cm^2. In contrast, our results showed considerably smaller wounds, which ranged between 39 (stand 51a) and 96.4 cm^2 (stand 59), likely due to less intensive technologies being used for timber removal. Indeed, in stand 9b, where a skidder was used to remove timber, the mean wound size reached 233.05 cm^2.

Jourgholami [30] stated that when a short-log method is used, the largest number of injuries (48%) occurred within 3 m of the trail centre. We obtained similar results, with between 32% and 57.7% of wounds occurring within two metres of the skid trail. Regarding the placement of the wounds on the stem, Tavankar et al. [22] stated that the mean percentage of wounds below 0.3 m was significantly higher than the means for 0.3–1 m and >1 m. Several researchers have also noted that most wounds occur at or near the base of the tree during logging [33,34]. We obtained similar results, as almost all wounds were located either on the roots or buttresses of the trees.

4.2. Bulk Density

Allmanová [35] analysed the changes in the soil bulk density in stands and ruts after the passage of universal tractors and forest skidders and found that, in both cases, the bulk density in ruts increased by 0.26 g·cm^{-3}. In our study, when a tracked mobile winch was deployed, the increase in BD was between 0.13 and 0.19 g cm^{-3}, though in stand 9b, where the skidder was deployed, the BD differences were similar to those in [35]. Kozlowski [36] reported that on soils previously not used for log skidding, the post-skidding BD increased by up to 52% at the 0 to 8 cm soil depth. Allman et al. [27] stated that compaction in the ruts of the trails increased by 30% to 35% when wheeled and by 25% when tracked machines were used. In our case, the differences showed the benefits of using smaller machines, because, in stands where the tracked mobile winch was used, the BD difference in ruts and the centre of the trails was considerably smaller than in the stand where a skidder was used. In relation to the variables that affect the BD increase, [37] stated that the trail slope correlated positively with the BD. In our case, a weak relationship was observed between the longitudinal slope and BD in the ruts. Kormanek and Dvořák [38] concluded that machine traffic contributed to the slight lowering of MC in the ruts in relation to the control. In our case, the highest MC values were recorded in the ruts of the technological trails. Other authors [39] studied the effects of forwarder traffic on soil surface attributes with various moisture contents and reached the conclusion that an indirect correlation exists between the bulk density and moisture content; i.e., the soil density decreases as moisture increases. In our case, the relationship between MC and BD was insignificant.

4.3. Penetration Resistance

Picchio et al. [37] reported that PR in undisturbed areas was significantly lower than in soils disturbed by machine traffic in their study focused on Hyrcanian and Camaldoli forests managed in a close-to-nature system and with skidder extraction. Kormanek and Dvořák [38] stated that PR was higher in the ruts compared to measurements next to and between the ruts when a tracked Entracon Sioux EH30 was used. Kruskal–Wallis tests showed similar results for the differences between PR in particular measurement locations in our case as well. Further, Picchio et al. [37] stated that the BD and PR were positively correlated, a result we were not able to confirm with our data.

5. Conclusions

Close-to-nature forest management is one of the options to increase the resilience and stability of forest stands to ongoing climate change. The change in the silvicultural approach also means changes to harvesting operations. The presented study analysed the disturbance of residual trees and forest soil in stands that are under reconstruction to multistorey, close-to-nature management.

We can conclude that:

- The intensity and character of wounds resemble those found in other management systems and operations; however, we attribute this to the relatively high intensity of harvesting due to the initial phase of the reconstruction. On the other hand, the size of the wound was smaller due to the denser network of technological trails and the cut-to-length logging method used.
- Soil disturbance in terms of BD proved to be the most severe in the ruts of the technological trails. However, the relative difference in BD between the control and ruts was considerably smaller than that observed when conventional technologies and machines were used. This was caused by the denser network of trails, as well as the use of smaller machinery for timber removal.
- Low-impact implementation of the close-to-nature management system requires the meticulous technological preparation of the workspace, the use of the cut-to-length logging method, and a dense network of technological trails to minimize the disturbance of soil and residual trees. Logging disturbances can endanger the productive capacity of the sites. Thus, a more extensive preparatory phase and organisation of the work are needed.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f14050910/s1, Table S1: Results of the Shapiro–Wilk and Levene's tests in the case of the variables II (%), IH (%), BD ($g \cdot cm^{-3}$), MC (%), PR (MPa), and PD (cm); Table S2: Comparison of BDs from the same measurement locations in different stands via multiple *p*-value comparisons; Table S3: Comparison of BD between different measurement locations in particular stands via multiple *p*-value comparisons; Table S4: Comparison of MC from the same measurement locations in different stands via multiple *p*-value comparisons; Table S5: Comparison of MC between different measurement locations in particular stands via multiple *p*-value comparisons; Table S6: Comparison of PR from the same measurement locations in different stands via multiple *p*-value comparisons; Table S7: Comparison of PR between different measurement locations in particular stands via multiple *p*-value comparisons; Table S8: Comparison of PDs from the same measurement locations in different stands via multiple *p*-value comparisons; Table S9: Comparison of PDs between different measurement locations in particular stands via multiple *p*-value comparisons.

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