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RESEARCH

Simultaneous negative changes in soil electrical resistivity and porosity in two Carpathian mixed forests induced by rubber-tyred skidder traffic

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Abstract

While the impact of forestry machinery on soil structure is well documented, large-scale monitoring of soil compaction in managed forests is hindered by the high spatial variability of soils, the labour intensity of conventional methods, and their time-consuming and destructive nature. These challenges obstruct the implementation of preventive strategies, such as optimised skid-trail design, to mitigate soil degradation. Meanwhile, efficient, non-destructive soil assessment techniques suitable for operational forestry remain underdeveloped. Here, we evaluate the potential of electrical resistivity tomography for detecting skidder-induced compaction in forest soils. Conducted in two Carpathian forests, the study employed two approaches: successive and spatially aligned soil electrical resistivity (ER) measurements before and after two loaded skidder passes in locality 1, and parallel ER measurements on a skid road formed by approximately forty passes alongside a non-trafficked area in Locality 2. Decreases of approximately 10 Ω m were observed after just two passes in locality 1 and > 200 Ω m after approximately forty passes in Locality 2, respectively. This study provides the first assessment of ER changes along forest skid trail sections almost 10 m long, accompanied by a soil porosity (φ) reduction of up to 13%. Significant effects of skidder traffic and locality on φ were indicated by two-way ANOVA ($p = 0.013$, $R^2 = 0.335$). Partial evidence for a significant co-occurrence of negative changes in both soil ER and φ was indicated by a probabilistic analysis under the assumption of independence ($p < 0.01$). However, higher φ sampling density, spatially aligned with soil ER variation, is required for a robust correlation analysis. These findings support the integration of ER tomography into forest operations as a decision-support tool while highlighting the necessity for diverse environmental conditions.

Keywords Forest soil monitoring · Forest operations · Soil compaction · Disturbance · Non-destructive soil assessment

Introduction

Soil sustains forest ecosystems and forest production, acting as a mediator in life cycles, including the flow of nutrients, water, and energy that sustain forest fertility and biodiversity (Dominati et al. 2010). Mechanised forest operations exert pressure on forest soils, which compromises the acceptability of forest management (Salmivaara et al. 2024). However, inadequate forest management practices during harvesting and silvicultural operations, such as logging, shelterwood cutting, and incremental thinning, lead to soil degradation processes, including soil compaction caused by the passage of increasingly heavy and powerful machinery (Latterini et al. 2024). As forestry machinery passes through, both horizontal and vertical pressures, cutting forces and vibrations

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are exerted on the soil (Alakukku et al. 2003). This leads to the alteration of the soil's physical state, the severity of which depends on various factors such as the vehicle's mass, weight on the axle/wheel/track, tire pressure, contact area between the vehicle and the soil, slope of the terrain, and dynamic cutting forces, along with soil characteristics and its moisture content (Jansson & Johansson 1998; Alakukku et al. 2003; Bygdén et al. 2004). The mass of forestry vehicles ranges from 5 to 40 Mg (Eliasson 2005), exerting their weight on the contact surface, the portion of the tire or track directly in contact with the ground. The size and shape of the contact area vary depending on tire deformation, influenced by tire characteristics, inflation pressure, wheel load, and soil plasticity (Hallonborg 1996). Pressure is not evenly distributed on the contact surface and can be significantly higher at certain points (Hillel 1998; Gysi et al. 2001). Machine-terrain interactions are extremely complex (Marchi & Certini 2014). Soil compaction is one of the criteria used to evaluate the environmental impact of agricultural machinery traffic on soil (Marsili et al. 1998) and has also been identified as one of the major problems causing soil degradation (Canillas & Salokhe 2002). Compacted soil layers caused by the passage of mechanical equipment during forest operations are the most common problem affecting seedling regeneration after forest harvesting. The variation in these soil physical parameters depends on many factors such as initial bulk density, moisture and organic matter content, and pressure exerted by the machines (Marchi & Certini 2014). The increase in bulk density is an obvious consequence of the reduction in total soil porosity (φ), which can amount to as much as 50–60% in some cases (Ampoorter et al. 2007; Picchio et al. 2012; Solgi & Najafi 2014). Soil compaction has significant consequences for soil functionality; in fact, soil compaction can reduce the access of plant roots and microorganisms to water, oxygen and nutrients (Picchio et al. 2020). Changes in porosity affect infiltration capacity (Homolák et al. 2010), plant-water relationships, aeration, and frost depth, limiting regeneration and creating a less favorable environment for plant growth (Currie 1984; Solgi et al 2019). Soil compaction also reduces air permeability, limiting gas exchange with the atmosphere and reducing oxygen availability for roots (Frey et al. 2009). Measuring soil bulk density and porosity as soil compaction indicators with the standard methods is both destructive and labour-intensive and time-consuming, especially challenging in large areas and at different depths (Brillante et al. 2015). Besides, methods based on soil sampling capture only a relatively limited soil volume around the points of measurement and may not account for the spatial variability of soil physical properties resulting from natural patterns and processes or anthropogenic activity (Hanxiao et al., 2022). Therefore, research is focusing on the use of indirect methods. Among non-destructive geophysical methods, the soil electrical resistivity (ER) tomography is capable of capturing both lateral and vertical soil ER variation and thus gathering continuous, two- or three-dimensional information, accounting for a considerable amount of the spatial and temporal variability of many soil-compaction-related soil physical properties (Samouëlian et al. 2005; Robinson et al. 2008; Calamita et al. 2012; Homolák et al. 2020). The soil ER tomography potential derives from the ER's dependence on soil bulk density, porosity, pore size distribution, pore connectivity, and soil water content (Jeřábek et al. 2017; Kowalczyk et al. 2014; Romero-Ruiz et al. 2018; Samouëlian et al. 2005). The 2D or 3D images of the ER distribution in the subsurface allow for the detection of resistivity contrasts that may be mainly due to lithological nature of soils, contact of soil particles with one another, and the variation in water content, as well as soil solute chemical composition. Soil compaction is mainly characterized by increased soil bulk density and reduced macroporosity, resulting in lower ER values. In this way, the soil ER can be used to estimate differences and both horizonal and vertical variations due to soil compaction at different depths (García-Tomillo et al., 2018; Jeřábek et al. 2017; Robinson et al. 2008; Zhu et al. 2007). In doing so, variations in soil moisture, on which ER depends to a large extents (Alamry et al. 2017), must be accounted for.

Thus far, patterns of lateral variations in ER were only identified on agricultural soil profiles and mostly in the direction perpendicular to the lines of tractor passages and further studies are needed to establish the concrete relationship between soil compaction and geophysical signals (Mansourian et al. 2024). As one consequence, the variation along the tracks could not be fully captured. For forest soils, soil ER profiles in the direction perpendicular to or aligned with the skid trails were not yet established. The objective of this study was to determine whether and how forestry traffic impacts ER signature on soil profiles aligned with the skid trails compared to non-trafficked forest soils. To achieve this, we chose profiles aligned with the skid trails to account for spatial variability, typical of forest soils (Seladji et al., 2010). Our working hypotheses were that (*i*) pre-post soil ER changes produced by as few as two forest skidder passes can be detected by ER tomography; (*ii*) ER changes on the profiles aligned with skidder tracks are both negative and positive but significantly dominated by the former; (*iii*) there is a relationship between soil ER and φ negative changes driven by the skidder traffic.

Material and methods

Experimental sites

The experiment was conducted in two forests in the central, volcanic part of the Inner Western Carpathians, in the Middle European Forest biogeographical province (Udvardy 1975). The first experimental area was Lubica (locality 1: N 48°31´01.873´´, E 019°13´48.997´´) was 5 km southeast of Zvolen, at 620 m a.s.l., with the average annual precipitation ranging from 800 to 900 mm and the yearly average temperature about 5 °C (Faško and Šťastný, 2002; Šťastný et al. 2002). The stand consists of European beech (*Fagus sylvatica* L.), aged 110 years, on a north-eastern slope with a 40% inclination. The second experimental area was Postarka (Locality 2: N 48°34´25.574´´, E 019°5´20.661´´located 2 km west of Zvolen in the Central Slovakia, at 350 m a.s.l. Its average annual precipitation varies from 700 to 800 mm, with an average yearly temperature between 7 and 8 °C (Faško and Šťastný, 2002, Šťastný et al. 2002). The forest stand, mainly comprising pedunculate oak (*Quercus petraea* Matt.) and hornbeam (*Carpinus betulus* L.) is 110 years old, growing on a gentle eastern 5% slope. The soils underlying both localities, found in the Tertiary volcanics of the Inner Western Carpathian, were Eutric Cambisols (acc. to WRB; FAO 2006) with 27–37% stony fraction, a silty-clayey-loamy texture, and an average bulk density of 1.29–1.35 g cm^{-3} in the top 0.4 m. They formed on bedrock and slope deposits consisting of Andesite and Andesite breccias and conglomerates. In the lower part of the locality 2, the soil substrate was mixed with gravels of fluvio-limnic origin. Owing to the nutrient-rich bedrock, tree species composition, and climate, the surface organic layer was relatively thin (Ol 3–5 cm, Of 0.3–1.5 cm, and Oh 0.0–0.3 cm).

Study design and soil physical properties measurement

At each of the two localities, several 9.3 m long electrical resistivity (ER) profiles were established in May and June 2024, according to the design scheme (Fig. 1, panels L, P). In the locality 1 (Lubica) located on a slope with a homogeneous, 40% inclination without microrelief features, the measurement took place during logging and skidding operations. Six ER profiles, each 9.3 m long, were taken: three ER profiles before skidder passes, and three profiles after two passes, on the same lines of measurement. The first pass was by the skidder pulling the attached logs uphill. The logs were attached to a skidder winch and pulled by LKT 81 tractor skidder with a total weight of 7.2 t. The logs volume pulled during each pass was approximately 4 m^3. After logs were attached, the skidder steered to achieve the alignment of wheel (tracks) with the lines of the soil ER measurement well before reaching them. During the uphill movement of the skidder, the logs remained centered mostly between the tracks. The second pass was by the unloaded skidder moving downhill. Thus, the pre-traffic ER profiles were acquired from an undisturbed soil (Fig. 1, L; Fig. 2, L1), later trafficked by a skidder loaded with logs (Fig. 1 L; Fig. 2, L2) and without logs. The skidder movement, aided by ground markings and research assistants, strictly followed the lines of the ER measurements. The post-traffic ER profiles were obtained on the same measurement lines, aligned with the skid trails resulting from the two passes by the skidder. In the second locality (Postarka), three ER profiles were taken on trafficked soil on skidder tracks, on a skidder road formed by log skidding during the previous year, and three profiles on adjacent parallel lines on measurement on a non-trafficked soil, 5 m from the skid road (Fig. 1, P). The number of skidder passes was around forty.

Soil moisture as the volumetric soil water content (SWC) (cm^3 cm^{-3}) was determined by the Time Domain Reflectometry (TDR) field operated meter (FOM/mts, Easy Test, Lublin, Poland) in three soil pits (profiles), located 5 m from

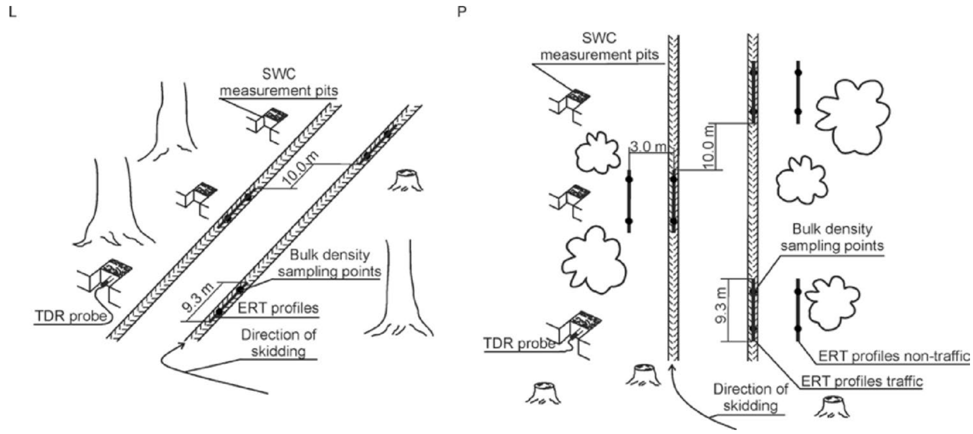

Fig. 1 The experiment design scheme on L) the inclined terrain (locality 1 – Lubica) and P) flat terrain (locality 2 – Postarka). Abbreviation: ERT – electrical resistivity tomography, TDR – Time Domain Reflectometry; SWC – Soil Water Content

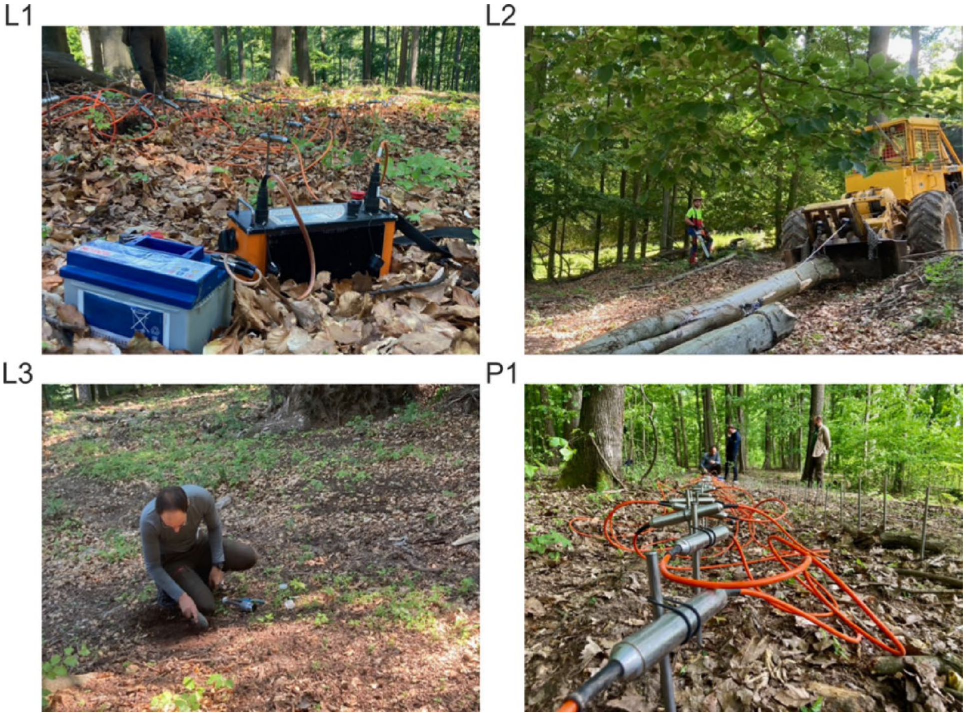

Fig. 2 Soil electrical resistivity measurement on a non-trafficked slope surface in locality 1 (L1); loaded LKT 81 tractor skidder pulling the beech logs in locality 1 (L2); topsoil sampling on skidder trails in locality 1 (L3); soil ER measurement on a skid road in locality 2 (L4)

the middle points of the soil ER profiles, at 0.10 and 0.20 m depth at each locality (Fig. 1). The TDR probe rods, inserted in the soil, were 0.11 m in length and the measurement was made at the beginning of the experiment. Soil texture was established by the pipette method on samples taken from 0.10 and 0.20 m depth. The ER measurements were conducted by ARES, an automatic geophysical system (GF Instruments, Brno, Czech Republic), with a unit electrode spacing of 0.30 m using a Wenner–Schlumberger array. At the beginning of the measurement, the potential was set to 20 mV, pulse to 0.5, measurement stacking to 4 (i.e., minimum and maximum pulses were both 4), and the number of data points was 225 for each measured profile. The measurement data were analyzed using the RES2DINV software, which employs the least squares method to smooth the data obtained from pseudo-sections (Loke 2000). To measure φ, 12 samples were taken from undisturbed soils at each of the two localities – six samples before the commencement of the skidding operation in locality 1, and six samples 5 m away from the skid road in locality 2. Also, at each of the localities, the same number of samples were taken from the trafficked soils, i.e. from the skid trails after the completion of the two passes in locality 1, and on the skid road tracks in locality 2 (Fig. 1, L, P). The samples were taken from the topsoil (0.05–0.10 m) using metal cylinder with an inner diameter of 50 mm and a volume of 100 cm^3 (Fig. 2, L3).

The samples bulk density was determined gravimetrically and the particle density by the pycnometric method. Soil porosity was then calculated according to $\varphi = 1 - \rho_d/\rho_s$, where φ is the soil porosity, ρ_s is the particle density of the soil (g cm^{-3}), and ρ_d is the bulk density of the soil (g cm^{-3}). Soil compaction was then calculated as the difference in porosity of the samples taken from the undisturbed and trafficked soils after the respective number of skidder passes.

Statistical analyses

Two-sample Kolmogorov–Smirnov test and one-sample *t*-test were used to examine possible differences between locations of the soil ER distributions at two successive soil depths, and the observed soil ER deviations from the hypothetical mean (ER change = 0), respectively. The Mann–Whitney *U* test (non-parametric) was used to test the soil ER differences on non-trafficked and trafficked terrain (skid road tracks) at locality 2 (Postarka). A two-way ANOVA, preceded by Levene's test of homogeneity of variances and the test for heteroskedasticity, was used to test the applicability of examining the effects of the locality (Lubica, Postarka) and skidder operations (non-trafficked, trafficked) on φ. A 2 × 2 between-subjects design (locality: Lubica, Postarka; traffic: non-trafficked, trafficked) was used with φ as the outcome variable. Owing to spatial (for φ) and interpolation resolution (for ER) limits, our φ and ER measurements were considered independently and not spatially pairable. However, their possible relationship between the soil ER and was studied through the joint extremity of the two variables as an indicator of the their potential association. The number of negative changes in soil ER and φ was treated as two independent binary outcomes across $N = 12$ unpaired observations, avoiding direct reliance on spatial coincidence

Table 1 Soil textural composition and volumetric water content at both localities

Locality	Depth (m)	Soil texture (%)				SWC (%)		
		N	> 0.063 mm	0.002–0.063 mm	< 0.002 mm	*N*	Average	SD
1 (Lubica)	0.10	3	23.76	57.47	18.78	3	21.77	2.24
	0.20	3	20.89	61.09	18.02	3	23.93	0.80
2 (Postarka)	0.10	3	17.08	63.78	19.14	3	16.80	1.04
	0.20	3	17.46	62.13	20.42	3	18.50	1.32

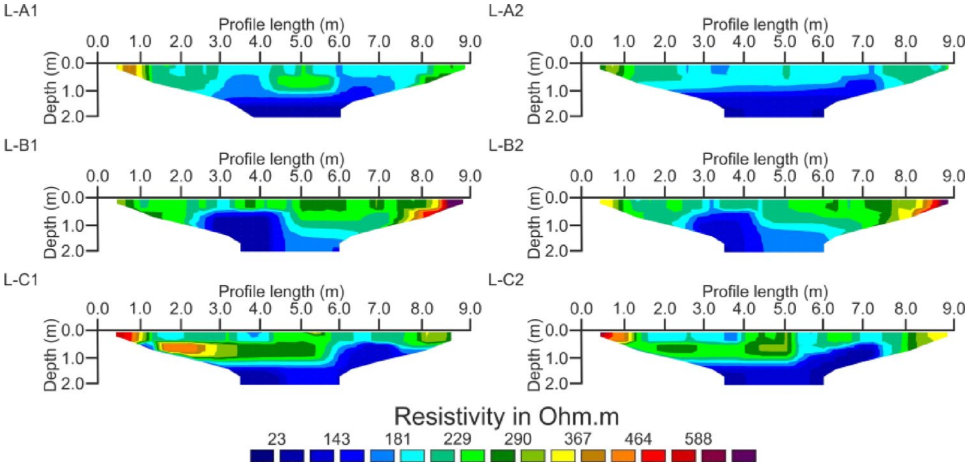

Fig. 3 Corresponding soil electrical resistivity profiles before (L-A1, L-B1, L-C1) and after two passes by rubber-tyred skidder (L-A2, L-B2, L-C2) in locality 1 (Lubica)

of the data, which could only be attained by a considerably higher sampling density and spatial resolution. Each variable was modelled as a binomial process with 12 trials and a success probability of 0.5, representing the assumption that negative and positive outcomes were equally likely under the null hypothesis. To evaluate the probability of simultaneous high counts of negative outcomes, the joint probability of independent outcomes was computed as the product of marginal binomial probabilities. This approach follows established null model strategies for evaluating co-occurrence under random expectation (Chang et al. 2023) and applies binomial logic for joint occurrence of independent binary events (Gotelli & Ulrich 2010). All statistical tests were conducted in SPSS, version 28.0.1.0 (Armonk, NY: IBM Corp.) and Wolfram Mathematica, version 13.0.0.0 (Wolfram Research, Inc., Mathematica, Champaign, IL).

Results

Soil physical properties

Texture and volumetric water content

The soil type at both localities was silty clay loam acc. to WRB (IUSS Working Group WRB 2022). The similarity of the two localities in terms of textural composition and forest vegetation cover determined their comparable SWC at the time of the experiment. The established minor difference resulted from an approx. 270 m altitudinal difference and thus a slightly higher precipitation amount. However, the volumetric SWC variability after several weeks of a relatively dry weather was low, as indicated by the SD values (Table 1).

Soil electrical resistivity

Figure 3 shows corresponding pairs of soil ER profiles located on the forest slope and determined before (L-A1, L-B1, L-C1) and after two rubber-tyred skidder passes (L-A2, L-B2, L-C2), one loaded and one unloaded. They represent the pre- to post traffic ER measurement mode employed at locality 1 (Lubica). The ER values in the locality 1 were generally lower than in locality 2 (Fig. 4). The difference is in line with the SWC that was by approximately 5% higher in the former area and contributed to lower soil ER.

The distributions of the pre- to post traffic ER changes for the locality 1 and the differences between trafficked and no-trafficked soils for the locality 2 in the ER tomography nodes for three soil depths are shown in Fig. 5 (panels L1–L3 and panels P1–P3, respectively). The average soil ER change deviations from the hypothetical mean (ER change = 0) ranged from –11.27 Ω m in the topsoil to –6.13 Ω m in the subsoil of (Table 2). According to one sample *t*-test, the soil ER changes were significant in the 0.00–0.15 m and 0.15–0.30 m, but not in the 0.30–0.45 m layer. The Kolmogorov–Smirnov test indicated no difference in the soil ER changes between the first two layers ($p > 0.10$) and a marginal difference for the third layer ($p < 0.089$). The

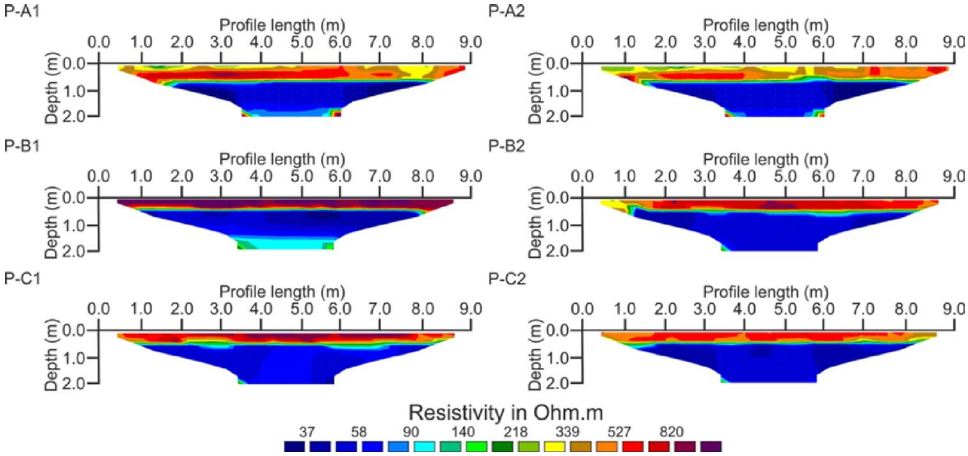

Fig. 4 Corresponding soil electrical resistivity profiles on the non-trafficked area (P-A1, P-B1, P-C1) and on a skid road formed by approx. 40 passes by rubber-tyred skidder (P-A2, P-B2, P-C2) in Locality 2 (Postarka)

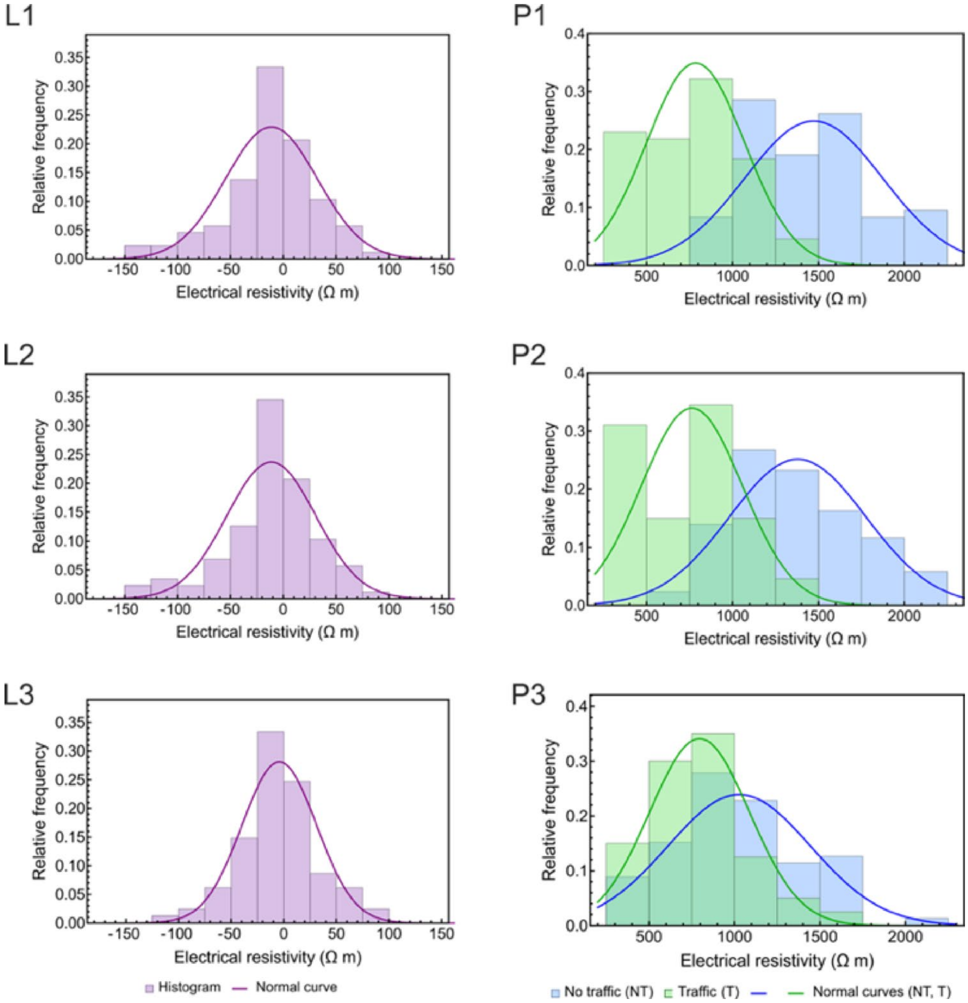

Fig. 5 Histograms of soil electrical resistivity (ER). Left column – ER changes in locality 1 (Lubica) at 0.00–0.15 m (L1), 0.15–0.30 m (L2), 0.30–0.45 m (L3); right column – ER of non-trafficked and trafficked surfaces in locality 2 (Postarka) at 0.00–0.15 m (P1), 0.15–0.30 m (P2), 0.30–0.45 m (P3)

Table 2 One sample *t*-test of the soil electrical resistivity (ER) difference deviations from the hypothetical mean (ER change = 0) at locality 1 (Lubica) and independent two-sample test between ER on non-trafficked and trafficked surfaces

Locality No	Soil layer depth (m)	*N*	Average soil ER change (Ω m)	Standard deviation	*t*	t_{krit}	*p*	Cohen *d*
1	0.00–0.15	87	–11.27	43.51	–2.42	1.99	0.017	0.26
	0.15–0.30	87	–11.35	42.11	–2.51	1.99	0.014	0.27
	0.30–0.45	81	–6.13	35.20	–1.56	1.99	0.121	0.17
Average			–9.58					

Table 3 Mann–Whitney *U* test of soil electrical resistivity (ER) differences at locality 2 (Postarka) on non-trafficked and trafficked terrain (skid road tracks)

Locality No	Soil layer depth (m)	*N*	Median ER (Ω m)		*U*	*z*	*P*	Effect size *r*
			Non-trafficked	Trafficked				
2	0.00–0.15	87	1444.90	794.64	275	9.67	< 0.001	0.73
	0.15–0.30	87	1363.60	780.57	821	8.92	< 0.001	0.68
	0.30–0.45	81	990.65	760.23	2158	3.76	< 0.001	0.30

Table 4 Soil porosity (φ) in the research localities

Locality	Traffic status	*N*	Average	Std. deviation
1 (Lubica)	Non-trafficked	6	0.52	0.09
	Trafficked	6	0.48	0.03
2 (Postarka)	Non-trafficked	6	0.49	0.02
	Trafficked	6	0.41	0.03

Table 5 Two-way factorial ANOVA of the effects of locality and forest skidder traffic on soil porosity

Source	df	*F*	*P*	η^2
Model	3	4.938	0.010	0.425
Locality	1	5.214	0.033	0.207
Traffic	1	8.681	0.008	0.303
Locality × Traffic	1	0.917	0.350	0.044

Cohen's *d* as an effect size measure reached 0.27 in the topsoil, indicating a small but noticeable skidder traffic effect on the soil ER. In the 0.30–0.45 m layer, the effect became non-significant. In the locality 2 (Postarka), Mann–Whitney *U* test of soil ER differences between non-trafficked soil and skid road tracks (Table 3) indicated that 40 passes caused a significant ER reduction in all three soil layers, although the differences and the corresponding effect sizes (*r*) diminished with depth, from 650.26 to 230.42 Ω m, and from 0.73 to 0.30, respectively. The topsoil *r* (0.73) suggests a large and practically meaningful effect of 40 passes and a moderate to small impact in the 0.15–0.30 m and 0.30–0.45 m layers.

Soil porosity

Average values of φ and their standard deviations are given in Table 4 showing that the difference between the two localities for non-trafficked soils was nominally smaller than for the trafficked soils, in which the effect of distinct number of skidder passes thus became apparent. At the same time, the contrast between non-trafficked and trafficked conditions is bigger for the second locality. These differences were further analysed as the effects of the locality (Lubica, Postarka) and skidder operations (non-trafficked, trafficked) through a two-way ANOVA. The Levene's test of homogeneity of variances ($p > 0.1$) and the test for heteroskedasticity ($p > 0.1$) indicated that the ANOVA assumptions were met. The overall two-way ANOVA model (Table 5) was statistically significant at $p = 0.010$, explaining a notable portion of the φ variation ($R^2 = 0.335$). The main effects of locality and soil condition were both significant at $p = 0.033$ and $p = 0.008$, respectively. Since the two factors had two levels each, Table 5 also indicates that an interaction between the two factors was not detected and so only main effects of skidder traffic and locality were analysed and shown to be significant (Table 6). The effect size $\eta^2 = 0.425$ (Table 5) indicates that the two factors (locality and skidder traffic) included in the ANOVA explain a very large portion of φ variability. Considered separately, skidder traffic showed a large ($\eta^2 = 0.303$) and locality a medium effect ($\eta^2 = 0.303$). It must be noted that while the traffic factor effect is responsible for the pre- to post-traffic difference in φ, the effect of locality accounts for the different numbers of skidder passes, rather than natural variability of φ, as also suggeted by the Table 4 data.

Relationship between soil ER and porosity

As mentioned, our measurements of soil ER and φ were not considered spatially pairable due to relatively low sampling density for φ, interpolated ER values, and the lack of correspondence between the scales of measurement for the two variables. Therefore, we evaluated the probability of their joint outcomes under the assumption of independence, using exact binomial models. This approach was appropriate for analyzing aggregate counts without location-specific matching. Of the 12 observations, at the two localities taken together, negative changes were observed in 10 cases for the soil ER and in 11 cases for φ. The joint probability of both variables independently showing at least

Table 6 Main effects of locality and forest skidder traffic on soil porosity given as a fraction of the total soil volume that is taken up by the pore space

Factor	Factor levels	Average	Mean difference	SE	*P*	95% CI
Traffic	Non-trafficked	0.507	–0.067	0.023	0.008	[–0.114, –0.019]
	Trafficked	0.440				
Locality	Locality 1 (Lubica)	0.499	–0.052	0.023	0.033	[–0.099, –0.004]
	Locality 2 (Postarka)	0.448				

10 negative outcomes was estimated at 0.04%, indicating that the observed co-occurrence is highly unlikely under the assumption of independence. These findings support the alternative hypothesis that ER and φ were associated in terms of their negative changes, produced by forest skidder traffic, under the conditions studied, despite the lack of spatial pairing between measurements.

Discussion

The overall results support the hypotheses that (1) pre- to post-traffic soil ER changes produced by two loaded skidder passes can be detected by ER topmography, (2) negative changes prevail on the soil ER profiles, and that (3) there is a probabilistic relationship between soil ER and φ reduction driven by skidder traffic.

Soil electrical resistivity

The ER measurements from both localities illustrate a relatively high spatial variability. The range of topsoil resistivity on non-trafficked (within the last 10 years) profiles in both localities was similar as in a Luvisol on schist (approx. 50–450 Ω m), but much lower than in a Cambisol on silty deposit (approx. 2000–3000 Ω m) (Paillet et al. 2010). The ER values in the Lubica soil were lower (around 200–300 Ω m) than in the Postarka (200–800 Ω), in line with a comparatively higher soil water content in the former locality. Despite considerable soil ER spatial variability, the ER tomography detected a small, approximately 10 Ω m decrease after only two skidder passes. The ER decrease was far more noticeable (>230 Ω m) after 40 passes in all soil layers. In terms of skidder traffic impact on the soils, the topsoil was affected strongly after 40 passes (r=0.73), and weakly (Cohen's d=0.27), but still noticeably, after only two passes. The impact became small to negligible in the 0.30–0.45 m layer. Our results are comparable to García-Tomillo et al. (2018), who established soil ER decrease by ca –40 Ω m in the top 0.1 m (but not deeper) after one passage by an agricultural tractor on Eutric Cambisol of metabasic rock.

Soil porosity

Nominal differences between φ at the two localities (Table 4) were bigger for trafficked (0.07) than non-trafficked (0.03) soil conditions. However, while the two-way ANOVA (Table 5) revealed significant main effects of the locality and traffic factors on φ, a significant interaction between the factors was not detected and, therefore, the analysis of simple effects was waived. The main effects of locality and traffic produced differences of –0.067 and –0.052 between trafficked and non-trafficked conditions, and locality 1 (Lubica) vs locality 2 (Postarka), respectively. This corresponded to approx. 13.2% φ reduction, less than 37% reported by Solgi et al. (2015) from broadleaved Caspian forests on a 20% slope, and slightly more than 8% after one pass by an unloaded skidder (Sadeghi et al. 2022). In terms of the influence of soil water content—17 to 24% —our results fit well in the middle of the φ reduction interval ranging from approx. 6% to 18% in dry (13%) and moist (25%) soils, established by D'Acqui et al. (2020). The reduction of φ in our localities was lower than approx. 30% found by Proto et al. (2016). Macrì et al. (2017) reported a 6% SR reduction, similar to our results, after 10 passes on an Umbrisol, featuring slightly lower SWC (14%) under a silver fir forest, with a lighter skidder (5.7 t vs 7.5 t).

Relationship between soil electrical resistivity and porosity under skidder traffic

Thus far, attempts to find clear relationships between the absolute value of ER and the degree of soil compaction through machinery—expressed through e.g. porosity reduction—have been rare and limited to agricultural soils, e.g. Keller et al (2017) or non-trafficked tropical forest soil (Farid et al. 2023). We established very high and simultaneous counts of negative outcomes in both soil ER and φ with an extremely low probability of co-occurrence by chance. The rare local instances when soil ER (2 cases) or φ (1 case) increased in the profile subsections can be explained by the variations of the pressure/release, forces, and vibrations exerted by the wheels on uneven and rough forest terrain surfaces, especially on the slope in locality 1 (Lubica). Local ER increases in agricultural soils ER after agricultural machinery traffic were reported by Keller et al. (2017) and Carrera et al. (2024). While our ER and φ measurements were not spatially pairable, modelling ER and φ as independent binomial variables provided a conservative statistical estimate of the likelihood of their co-occurrence under random expectations. The aggregate-level co-occurrence suggests that the soil ER and φ responses to skidder traffic as a shared driver of underlying soil environmental processes were not mutually independent. The direction of the relationship (lower soil ER at smaller φ) aligns with that reported by Farid et al. (2023) for a non-trafficked tropical forest area, and Kowalczyk et al. (2014) for laboratory non-cohesive soils.

In summary, our study demonstrates that changes in soil electrical resistivity caused by just two loaded skidder passes can be reliably detected using ER tomography, even in spatially variable forest soils. We also show that these changes are predominantly negative and coincide with measurable reductions in soil porosity (φ). While soil ER and φ were measured at different spatial scales and could not be directly paired, a statistically rare co-occurrence of negative changes indicates a non-random, likely mechanistic relationship between them. This finding strengthens the evidence that both physical and structural soil properties respond jointly to compaction from forest machinery, offering a conservative yet robust tool for assessing early-stage soil disturbance in forest operations.

Study limitations

The absolute soil ER values in this study pertain only to soils derived from their respective substrates. Considerable ER differences between the two localities in which our research was conducted also reflected the generally high variability of the field conditions, including SWC, ambient temperature, and soil geometry and moisture. I addition, the precise types of skidders and tyres used in multiple skidding cycles in the locality 2 were not known, although they could further contribute to inter-site variability alongside other sources of error, such as that caused by electrode arrangement on uneven surfaces. It is therefore obvious that the soil ER survey can currently be used for establishing relative changes in φ, but not the absolute values without local calibration. Because of this, as well as the lack of precise depth-specific data for φ in the ER profiles, our analysis of the relationship between ER and φ used binary outcomes and a probabilistic approach that does not require a fully specified contingency but leans on independent Binomial (12, 0.5) processes for both ER and φ.

Management implications and future directions

Our findings indicate that even a limited number of passes by a loaded skidder negatively affects φ and thus related soil properties, such as infiltration capacity, aeration, and root growth. This is highly relevant since the skid trail or skid road density often reaches > 50 m ha^{-1} in commercial forests (Đuka et al. 2017; Šebeň, 2017). While a well-developed skid-trail network may help avoid an uncontrolled expansion of forest machine traffic in the forest stand and thus reduce the disturbance of forest soil (Contreras et al. 2016; Đuka et al. 2017), its proper design would benefit from the application of the ER tomography method. Such an approach, using the established significant change of resistivity corresponding to the change in compaction, earlier found in laboratory conditions (Kowalczyk et al. 2014), or the local spatial variability of ER and mutual comparison of its values through, e.g., analytical hierarchical process (Coulter et al. 2006), would help to avoid unnecessary or excessive skid trail network development or overuse, eventually producing strong and naturally irreversible soil compaction. For example, older skid trails, covered by recent forest litter, could be identified and used for ground-based timber harvesting operations instead of establishing new routes. However, due to common economical constraints in the practical forestry, areas on steep slopes, soils sensitive to compaction and landslides, and protected areas under a management regime should be prioritised. Future research should study opportunities for full bivariate ER – φ relationship analysis, such as enhanced depth-wise φ sampling density.

Conclusions

Repeated soil ER tomography measurements on profiles overlapping longitudinally with the skidder tracks proved sensitive enough to reveal that even a small number of a loaded, rubber-tyred skidder passes can significantly alter the ER and porosity of a forest soil. An established binary marginal relationship that emerged between reduced porosity and lower soil ER underscores the method's potential for the monitoring of φ and diagnosing soil compaction alongside the feasibility of further field-based research. The study findings advocate for the minimization of skidder traffic to be achieved through strategic skid-trail design, involving soil ER tomography-produced data to mitigate damage and preserve vital soil functions in managed forests.

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Data availability Data availability upon a reasonable request to the corresponding author.

Declarations

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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