

Article

Assessing the Impact of Forest Machinery Passage on Soil CO₂ Concentration

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Abstract: Forestry machinery plays a key role in forest management, but its increasing weight significantly impacts soil condition. Machinery passage causes soil compaction, which alters the physical, chemical, and biological properties of the soil and affects CO₂ concentration. This study aimed to measure the impact of soil compaction on the evolution of CO₂ concentrations over three years. Research was conducted near Zvolen, Slovakia, where soil was compacted in 2020 by a forestry skidder. The intensity of compaction was evaluated using a digital penetrometer. CO₂ concentrations were measured with a Vaisala MI70 device, with 22 measurements taken post-compaction at an average interval of 52 days. Soil compaction was characterized by a derived penetration index. At a depth of 10 cm, the average penetration index was 119%, indicating a 19% increase in resistance. The highest index, 134%, was found at a depth of 3 cm. A correlation of 0.4 was found between the number of passes and CO₂ concentration at 30 cm depth, and 0.8 between penetration index and CO₂ concentration. Results showed a significant impact of forestry machinery on soil CO₂ concentration, even three years later. Therefore, operating practices should minimize machinery impact on forest soils.

Keywords: soil compaction; CO₂ concentration; forest management; skidder traffic; soil penetration resistance



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1. Introduction

The mechanization of forestry operations is unavoidable because it provides benefits in reducing costs and manual labor and efficient timber production. The passage of forestry machinery causes soil compaction, leading to significant changes in soil structure and moisture content [1–4]. The severity of soil compaction caused by machinery operation varies depending on the type of forest machine used and applied harvesting method, the frequency of machine operation, and soil characteristics [5–7]. The slope of the terrain and the intensity of traffic are the main factors that determine the soil compaction caused by machinery operation [8,9]. It is known that the slope of the terrain has an important influence on the ruts created by forest machinery [10,11].

Poor aeration of soil caused by soil compaction prevents the development of root systems and limits the water permeability of roots [3,12,13]. Concentration of CO₂ serves as an indicator of soil degradation caused by forest mechanization [14]. Some works show it is a more sensitive indicator of compaction compared to bulk density and penetration resistance [15]. The concentration of CO₂ in the soil organic horizon is only slightly higher than in the atmosphere [2]. As soil depth increases, the CO₂ concentration rises [16,17] and is accompanied by a significant reduction in oxygen (O₂) levels [18]. Seasonal variations of soil characteristics significantly influence soil CO₂ concentrations. The highest soil CO₂ concentrations are recorded at the end of summer, while the lowest values occur during winter, demonstrating a pronounced seasonal pattern [1,2]. The balance between CO₂ and O₂ varies based on the soil water content and biological activity and directly affects root growth [18].

The objective of this study was to examine the impact of soil compaction, induced experimentally using forestry machinery, on soil CO₂ concentration. We hypothesized that soil compaction would result in higher soil CO₂ concentration. In addition to soil CO₂ concentrations, we assessed soil temperature, soil moisture, the number of machinery passes, and soil penetration resistance and analyzed the relationships between soil CO₂ concentrations and these observed variables.

2. Materials and Methods

2.1. Site Description

The research site was located within the University Forest Enterprise of the Technical University in Zvolen, Slovakia (Figure 1).

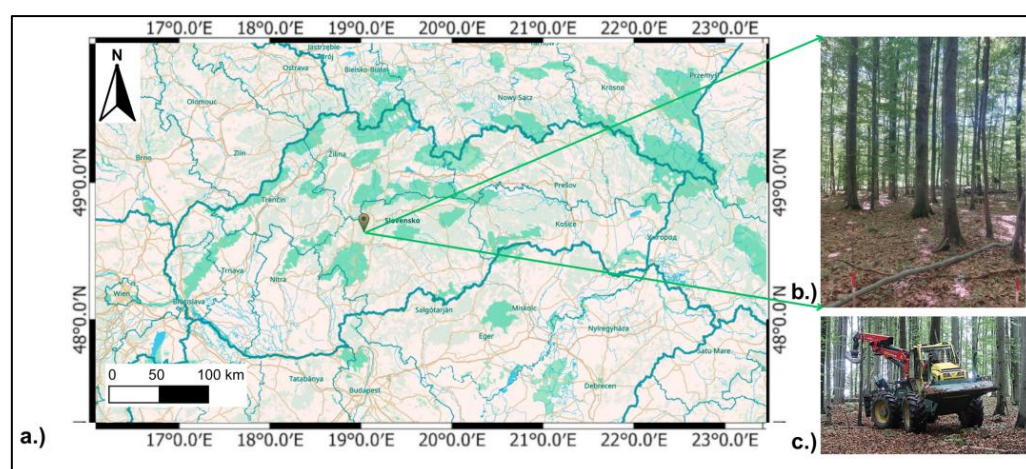


Figure 1. (a) Geographical position of the research plot within Slovakia. (b) Detail of the permanent research plot. (c) Forestry skidder (LKT 81 ITL) used for soil compaction.

The permanent research plot (PRP) with dimensions 60 × 25 m was established in 2020. Measurements were carried out in stand No. 554 (48°38′35.5″ N 19°02′12.5″ E) at the locality “Stagiar”. Basic stand and site characteristics, along with key soil parameters, are summarized in Table 1. The study area belongs to a moderately cold and very humid climatic region of Slovakia. The long-term mean annual temperature is 6.6 °C. The monthly temperature varies from −4 °C in January to 16 °C in July, and the average annual precipitation is 850 mm [19].

Table 1. Basic stand and site characteristics and soil parameters [20].

Stand Characteristic	
Stand No.	554
Age (years):	95
Area of stand (ha)	5.82
Stocking degree	0.87
Slope (%)	20
Aspect	West
Management system	Shelterwood
Altitude (m a. s. l.)	710
Tree species composition (%)	<i>Fagus sylvatica</i> L. (73); <i>Abies alba</i> Mill. (24), <i>Picea abies</i> (L.) H. Karst. (3)
Skidding distance (m)	50
Soil type	Cambisol
Soil texture	Silt Clay
Site Characteristic	
Tree species composition (%)	<i>Fagus sylvatica</i> L. (95); <i>Abies alba</i> Mill. (5)
Slope	0%–5%
Loam content (<0.002 mm) (%)	4.5
Silt content (0.002–0.063 mm) (%)	69.13
Sand content (0.063–2 mm) (%)	26.82

2.2. Experimental Design

The experimental soil compaction was conducted in June 2020. The PRP consists of two sub-plots: a control sub-plot and a compacted sub-plot (treatment with a forestry skidder—LKT 81 ITL was applied). Each sub-plot was 625 m² large (25 × 25 m). The tractor route within the plot was randomized. The machine drove at a walking pace over the soil surface unloaded to maintain consistent weight during the passage. Both the route and the traffic intensity (i.e., the number of passes) of the tractor were documented manually and recorded using GPS. During the manual drafting of the tractor route, orientation was guided by the positions and numbers of the trees. Given the inaccuracy of the GPS recording, which was affected by the dense tree canopy, a hand-drawn representation was ultimately utilized. The drawing was vectorized and georeferenced using QGIS software version 3.14 [21]. The traffic intensity was described as the number and length of passes within a 1 × 1 m square. Importantly, the compaction process was conducted under controlled experimental conditions and was not a part of a timber harvesting operation. In addition to measuring soil CO₂ concentrations, we assessed soil temperature, soil moisture, the number of machinery passes, and soil penetration resistance. Subsequently, we analyzed the relationships between soil CO₂ concentrations and these observed variables. Thanks to the three-year duration of the experiment, we were able to investigate the dynamics of soil characteristics, including temperature, moisture, and CO₂ concentration, as well as their temporal development following the soil compaction event.

Tire pressure was measured with a Pneurex 1 portable tire pressure regulator (Blitz Co., Ltd., Bräunlingen, Germany). A DINI ARGE0 3590 E axle scale with two WWSE10T load cells (700 × 450 mm; capacity 10,000 kg) was used to determine the machine weight. Technical parameters of the forestry skidder—LKT 81 ITL—are shown in Table 2.

Table 2. Technical parameters of the forestry skidder LKT 81 ITL.

Engine	Hydraulic Manipulator	Machine Width (cm)	Front/Rear Tires (inch)	Tires Type	Tire (Front/Rear) Inflation Pressure (MPa)	Front Axle Weight (kg)	Rear Axle Weight (kg)	Total Mass (kg)
JCB 448 TA1(JCB Power Systems, Derby, UK)	Epsilon M90 R72	250	540/70–30	Nokian Forest King	2.0/2.4	4230	6370	10,600

2.3. Soil Physical and Chemical Properties

To determine the soil texture in the forest stand, soil samples were collected and analyzed in the laboratory to quantify the proportion of fine fractions below 0.063 mm (clay, silt, and sand) using the Casagrande method. Soil samples were taken from half of the points at which penetration resistance was measured (Figure 2). Soil samples were collected up to 50 cm deep using steel cylinders (6 cm diameter, 100 cm long) to determine particle size fractions (0–0.25 mm, 0.25–2 mm, 2–4 mm, and >4 mm) at each soil layer defined by the depth. The sampled soil was divided into five layers, each 10 cm wide. After the division, the samples from different soil layers (0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, and 40–50 cm) were evaluated in the laboratory using the particle size analysis and bulk density test.

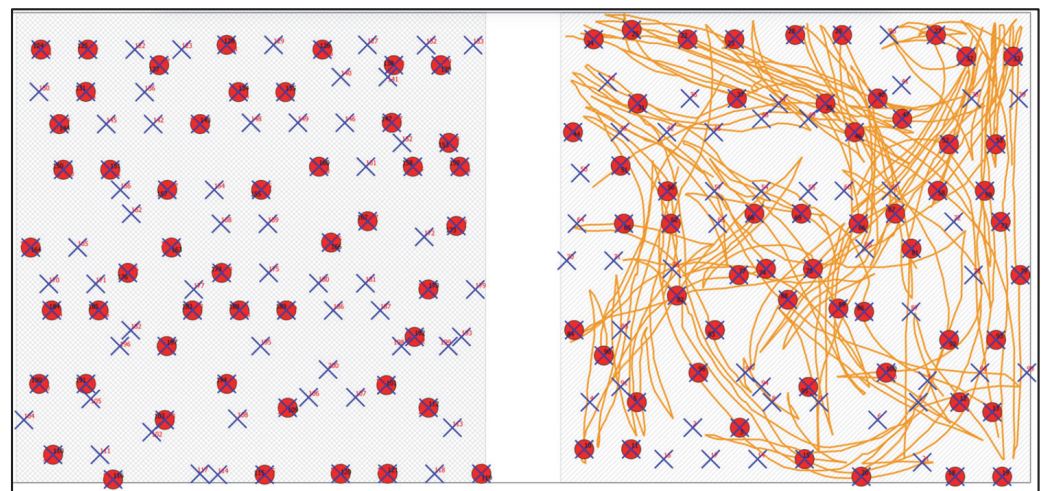


Figure 2. Permanent research plot (PRP) Stagiar: control sub-plot (left), compacted sub-plot (right). Red circles—soil sampling locations; blue X—location of penetrometer measurements; and orange lines represent tractor passages.

2.3.1. Measurement of Soil Penetration Resistance

Penetration resistance (PR) measurements were carried out in June 2020 using a digital penetrometer (Eijkelkamp Penetrologger 0615SA, Giesbeek, The Netherlands) from the Royal Eijkelkamp Company. The penetrometer was equipped with an 80 cm long rod and a cone with a diameter of 11.3 mm, an area of 1 cm², and an angle of 30°. The penetration rate was 2 cm s^{−1}. The penetrometer was fitted with a new cone before each measurement. The data were first stored in the memory of the instrument, from where they were exported to the computer using the Eijkelkamp Penetroviewer software 6.0. Penetration resistance data were processed in the statistical program R Version x64 4.0.3 [22].

PR values were measured in megapascals (MPa) at 1 cm depth intervals until solid rock was reached. PR values were obtained from both compacted and control sub-plots. At the compacted sub-plot, measurements were taken once before compaction (BC) and once

after the compaction (AC) treatment, and the penetration index Equation (1) was calculated based on the difference between these two measurements. The number of measurement points to detect the PR was 100 on both the compacted and control sub-plots in a 2.5×2.5 m systematic grid.

Soil compaction was quantified using the penetration index, calculated as follows:

$$\text{Penetration index} = \frac{\text{After Compaction (AC)}}{\text{Before Compaction (BC)}} \times 100 \quad (1)$$

This index represents the relative change in penetration resistance as a result of soil compaction. A value of the penetration index above 100% indicates an increase in resistance, while values close to 100% indicate minimal change. In this study, the penetration index was used to evaluate the impact of soil compaction across various depths within the compacted sub-plot. It enabled a quantitative comparison of soil resistance before and after compaction within the compacted sub-plot.

2.3.2. Carbon Dioxide (CO₂) Concentration, Temperature, and Moisture of Soil

The measurements were carried out at the permanent research plot, each time using two probes, one of which was placed in the soil compacted by the passage of a tractor; the other served as a control probe placed in the natural, undisturbed soil. At each sub-plot, 30 points were established near the points that were used for soil sampling. The distribution of points over the research plot followed the principles of stratified sampling, considering canopy coverage and the number of passages at the compacted sub-plot. The points at the control and compacted plots were paired if they were characterized with similar canopy cover and if the distance between them was below 30 m due to technical constraints. A representation of the individual pairs at which CO₂ and temperature measurements were made is shown in Figure 3. The measurements were carried out using the Vaisala MI70 instrument and the following probes: the GM70 Carbon Dioxide Probe to measure CO₂ concentration and the Vaisala Handheld HM70 Humidity and Temperature Probe to measure soil temperature and relative moisture of soil. Probes for CO₂ measurements can detect CO₂ concentration in the range of min. 0 to max. 5%. The changes in temperature, relative moisture, and CO₂ concentration were measured at the same points within the sub-plots over a period of 3 years after compaction.

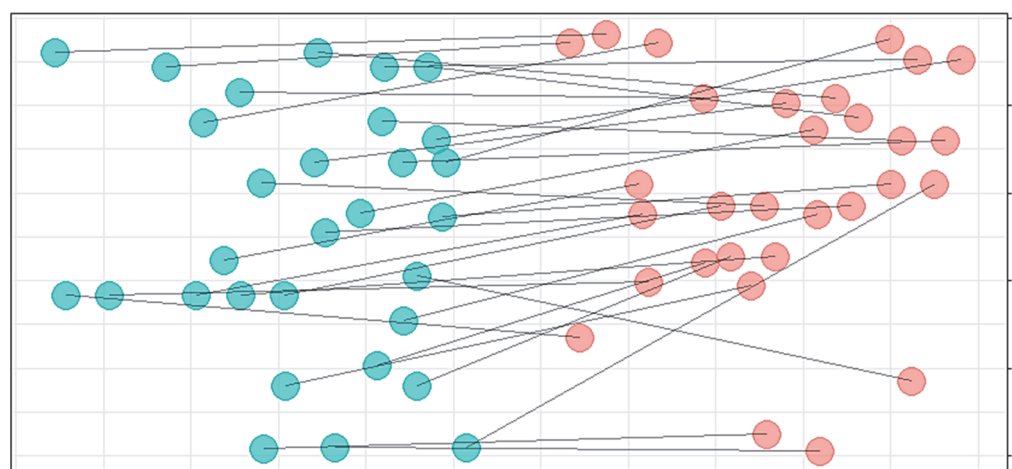


Figure 3. Pairs of points used for CO₂ measurements (green points located at the control sub-plot, red points located at the compacted sub-plot) and sampling design of the measurements within the PRP Stagiär.

At each point, measurements were carried out at soil depths of 10 cm and 30 cm. Temperature and CO₂ measurements were performed for all pairs of points at regular time intervals to capture the trend throughout the year (seasonal trend) in order to track differences between the compacted and control sub-plots. The measurement procedure was as follows: before the first measurement, the probe was left to stabilize for at least 20 min to ensure that the measuring sensor was adjusted to the soil conditions. During the first round of measurements, soil temperature was measured at a depth of 30 cm every 30 s for 5 min. After the first measurement round, the soil temperature and soil moisture values were set into the CO₂ measuring instrument. The second round of temperature measurements was performed at a depth of 10 cm. Similarly, the first round of CO₂ measurements was performed at a depth of 30 cm, then at a depth of 10 cm. The CO₂ measurements also took 5 min. Each time the probe was moved to the next point, the probe was allowed to stabilize to adjust to the conditions. The stabilization duration depended on the distance of the points and the temperature and CO₂ differences between the soil and the external environment. It takes approximately 5–7 min for the probe to stabilize.

2.4. Statistical Analysis

Data processing, organization, and statistical analyses were conducted using RStudio (Version 2023.12.1 Build 402) [22]. For data manipulation and preparation, the dplyr package was used, which provides functions such as mutate(), select(), filter(), and summarize(). One-sample *t*-tests were used to calculate the means and 95% confidence intervals (CI95%) for each variable to determine variability of soil characteristics within each sub-plot. To assess differences in mean values between sub-plots, the Welch two-sample *t*-test was applied using the t.test() function. Analysis of variance (ANOVA) was used to evaluate the effects of categorical variables (“Sub-plot” and “Layer”). ANOVA was performed using the aov() function, and summary statistics were obtained with the summary() function. Spearman’s correlation analysis was used to examine the relationships between penetration index, number of passages, soil temperature, soil moisture, and soil CO₂ concentration. The Seasonal-Trend Decomposition using Loess (STL) function was used to analyze long-term and seasonal trends in soil CO₂ concentrations, which allows decomposition of the time series into seasonal, trend, and residual components. This method is particularly suitable for environmental datasets with non-linear seasonal patterns. The decomposition was performed using the stl() function. For data visualization, the ggplot2 package was used, specifically the ggplot() function [22].

3. Results

3.1. Homogeneity of Soil Condition Within Sub-Plots

The analysis of soil homogeneity across the study area indicated that the observed characteristics were consistent throughout the permanent study plot. The results of the analysis of variance (ANOVA), including the interaction between the factors “Sub-plot” and “Layer,” revealed no statistically significant differences between sub-plots ($p > 0.05$, Table 3), suggesting uniform soil conditions within the study area.

Table 3. Comparison of soil characteristics between sub-plots (one-sample *t*-tests used to compute 95% confidence intervals (CI95%) for each variable). Adjusted *p*-values derived from ANOVA interaction between the factors Sub-plot and Soil Depth (Layer), *n* = 50 (Compacted), *n* = 50 (Control)).

Parameter	Mean $\pm$ CI95% <i>p</i> -Value					
	Soil Depth 0–10 cm		Soil Depth 10–20 cm		Soil Depth 20–30 cm	
	Control Sub-Plot	Compacted Sub-Plot	Control Sub-Plot	Compacted Sub-Plot	Control Sub-Plot	Compacted Sub-Plot
Bulk density [kg·m ^{−3}]	714.8 $\pm$ 47.88	800.85 $\pm$ 54.07 0.177	1065.86 $\pm$ 38.93	1078.58 $\pm$ 48.2 0.680	1197.57 $\pm$ 36.51	1204.64 $\pm$ 42.16 0.800
Fine solid soil fraction < 0.025 mm [%]	68 $\pm$ 3.2	63 $\pm$ 2.96 0.703	71.24 $\pm$ 3.2	65.09 $\pm$ 3.01 0.416	68.4 $\pm$ 4.34	66.94 $\pm$ 3.36 0.100
Fine solid soil fraction $\geq$ 0.025 mm $\leq$ 2 mm [%]	13.27 $\pm$ 1.72	15.13 $\pm$ 1.47 0.730	11.42 $\pm$ 1.25	12.91 $\pm$ 1.06 0.912	11.36 $\pm$ 1.64	12.24 $\pm$ 1.02 0.999
Fine solid soil fraction > 2 mm $\leq$ 4 mm [%]	3.46 $\pm$ 0.5	3.29 $\pm$ 0.44 0.999	2.7 $\pm$ 0.38	2.47 $\pm$ 0.34 0.999	2.75 $\pm$ 0.63	2.48 $\pm$ 0.41 0.999
Fine solid soil fraction > 4 mm [%]	11.16 $\pm$ 2.16	14.45 $\pm$ 3.33 0.964	13.95 $\pm$ 2.97	18.76 $\pm$ 3.21 0.731	17.14 $\pm$ 3.91	17.98 $\pm$ 3.64 0.999
	Soil Depth 30–40 cm		Soil Depth 40–50 cm			
	Control Sub-plot	Compacted Sub-plot	Control Sub-plot	Compacted Sub-plot		
Bulk density [kg·m ^{−3}]	1239.53 $\pm$ 46.29 0.776	1248.54 $\pm$ 43.4	1242.05 $\pm$ 37.41	1214.4 $\pm$ 59.72 0.432		
Fine solid soil fraction < 0.025 mm [%]	67.84 $\pm$ 5.15 0.449	61.66 $\pm$ 4.74	64.73 $\pm$ 4.84	61.61 $\pm$ 4.22 0.985		
Fine solid soil fraction $\geq$ 0.025 mm $\leq$ 2 mm [%]	11.11 $\pm$ 1.61 0.222	13.87 $\pm$ 1.65	14.17 $\pm$ 1.96	15.93 $\pm$ 1.45 0.842		
Fine solid soil fraction > 2 mm $\leq$ 4 mm [%]	2.4 $\pm$ 0.43 0.946	2.88 $\pm$ 0.56	3.31 $\pm$ 0.73	3.47 $\pm$ 0.66 0.999		
Fine solid soil fraction > 4 mm [%]	17.97 $\pm$ 4.94 0.971	21.26 $\pm$ 5.1	17.39 $\pm$ 4.46	18.52 $\pm$ 4.09 0.999		

3.2. Penetration Resistance

The variation in penetration resistance, represented as the average value across penetration points with the increasing soil depth at the compacted sub-plot, is presented in Figure 4. The results indicated a notable increase in penetration resistance following soil compaction, with resistance rising throughout the soil profile.

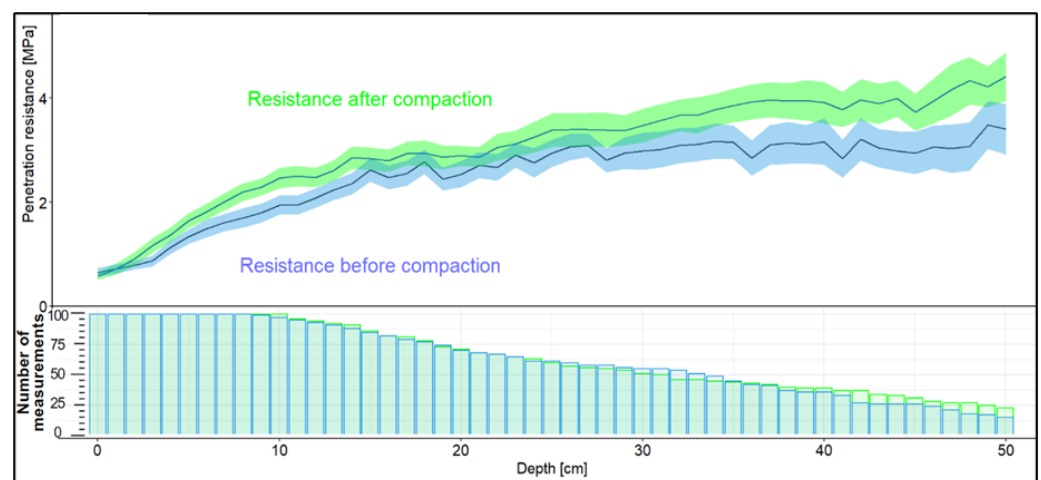


Figure 4. The effect of compaction on penetration resistance within a compacted sub-plot. The solid lines through the center of the colored buffer represent the mean values at respective depths, with a 95% confidence interval displayed in color around the mean.

The increase in PR within the compacted sub-plot was quantified by the penetration index, as depicted by the red curve in Figure 5. The average value of the penetration index for soil up to a depth of 10 cm was 119%, reflecting a 19% increase in penetration resistance caused by the skidder passage. In the topsoil, the maximum penetration index was observed at a depth of 3 cm, reaching 134%. Beyond a depth of approximately 15 cm, the penetration index began to decline; however, the difference in penetration resistance showed another upward trend at a depth of around 35 cm, continuing up to 50 cm.

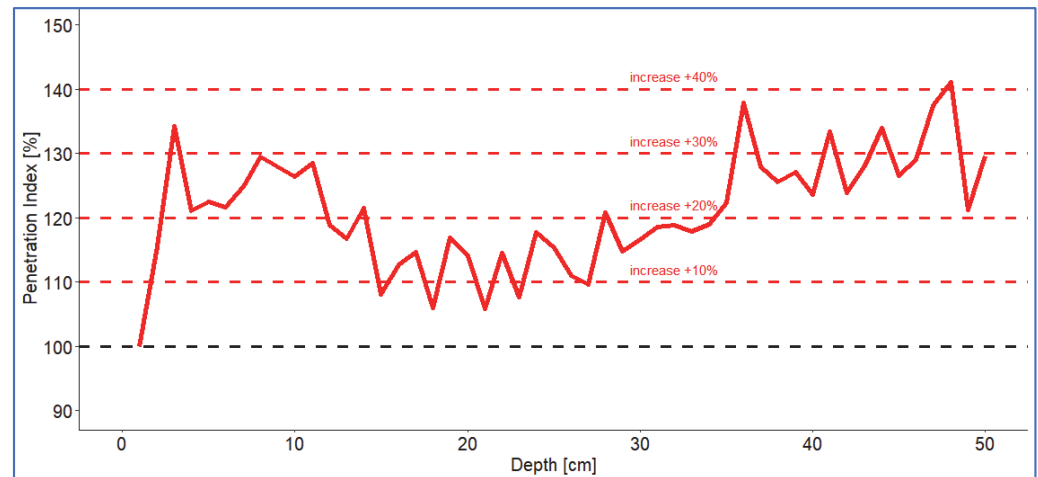


Figure 5. The effect of compaction on penetration resistance represented by the penetration index along the soil profile.

3.3. Concentration of CO₂ in the Soil

Soil temperature and soil moisture, as the primary abiotic factors influencing CO₂ concentration in soil, contributed to a noticeable seasonal trend, particularly at the compacted sub-plot. Higher CO₂ concentrations were recorded during the growing season, while both the variability and concentration of CO₂ reached their lowest levels during the winter months. The differences between sub-plots were less pronounced in the winter compared to the growing season (Figure 6).

Statistical analysis revealed significant differences in CO₂ concentration at 30 cm depth between the two sub-plots in most months ($p < 0.001$), with the exception of March 2022, when no significant difference between the sub-plots was detected. In December 2021, the difference was statistically significant at a lower threshold ($p < 0.05$). At a depth of 10 cm (as shown in the upper part of Figure 6), the differences between the control and compacted sub-plots were less pronounced. During the first year after compaction, the compacted sub-plot exhibited higher CO₂ concentrations. However, this trend reversed during the following year, with the control plot showing higher CO₂ concentrations from autumn 2021 until early summer 2022. In April 2022, the concentrations began to equalize between the plots, a trend that persisted until the onset of the 2023 growing season. In instances where statistically significant differences between means were observed ($p < 0.001$), the compacted sub-plot typically exhibited lower CO₂ concentrations at a depth of 10 cm, particularly during the months of November 2021, December 2021, January 2022, and March 2022. Conversely, statistically higher CO₂ concentrations at a depth of 10 cm at the compacted sub-plot were primarily observed in the early months following compaction (November 2020, December 2020, June 2020, July 2020, and September 2020). Beyond this period, differences either diminished or reversed, as previously noted. After 18 months following compaction, the differences at a depth of 10 cm were minimal and statistically insignificant. This suggests that within two years after the forestry machine's passage, the

CO₂ concentration at 10 cm depth returned to levels comparable to those of the control sub-plot, indicating the soil recovery at the compacted sub-plot.

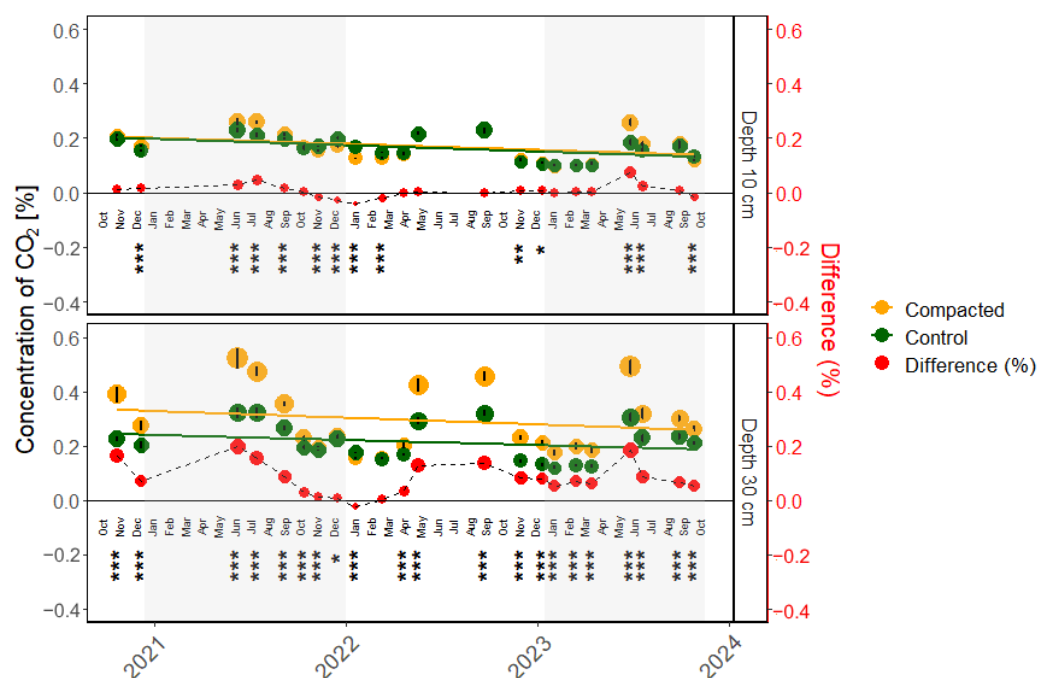


Figure 6. Comparison of mean CO₂ concentrations at the control (green) and compacted (orange) sub-plots, including the differences (red) between the sub-plots at depths of 10 cm and 30 cm. The size of each point represents the mean CO₂ concentration value, while the black vertical lines within the points represent 95% confidence intervals of the mean that indicate variability of measured values. Significant differences between the sub-plots are indicated as follows: 0.001 '***', 0.01 '**', 0.05 '*'.

Figure 7 illustrates the variability observed at individual measurement points, depths, and sub-plots over time. CO₂ accumulation was primarily observed during the growing season. At the compacted sub-plot, CO₂ concentration at a depth of 30 cm ranged from 0.049% to 1.250%, with an average value of 0.281%, while at a depth of 10 cm, the concentration ranged from 0.048% to 0.637%, with an average of 0.165%. At the control sub-plot, CO₂ concentration at a depth of 30 cm varied between 0.054% and 1.160%, with an average value of 0.206%. At 10 cm depth, the values ranged from 0.057% to 0.470%, with an average of 0.163%. Over the measurement period from October 2020 to October 2023, a slight decline in CO₂ concentration was observed at both plots and both soil depths. Notably, higher CO₂ concentrations were recorded at a depth of 30 cm at both compacted and control plots.

The results indicate that CO₂ concentration at a soil depth of 10 cm was lower than at 30 cm, although a seasonal trend was still evident at both depths. Figure 8 illustrated the positive correlation between CO₂ concentration at 30 cm and relative moisture at both 30 cm and 10 cm ($r = 0.7$ for each). The weak correlation ($r = 0.1$) between CO₂ concentrations at 30 cm and 10 cm depths suggests that gas dynamics in the upper and lower soil layers were influenced by different factors, which can explain the relatively small transfer of CO₂ between these depths. Greater differences between sub-plots were observed at 30 cm depth.

The STL decomposition of soil CO₂ concentrations revealed a distinct seasonal trend—seasonal component (Figure 9). The seasonal component exhibited pronounced peaks in CO₂ concentration during the growing season, whereas the winter months were characterized by lower CO₂ levels and reduced variability. The trend component demonstrated a consistent decline in CO₂ concentration over a three-year period following compaction, as illustrated by the trend line.

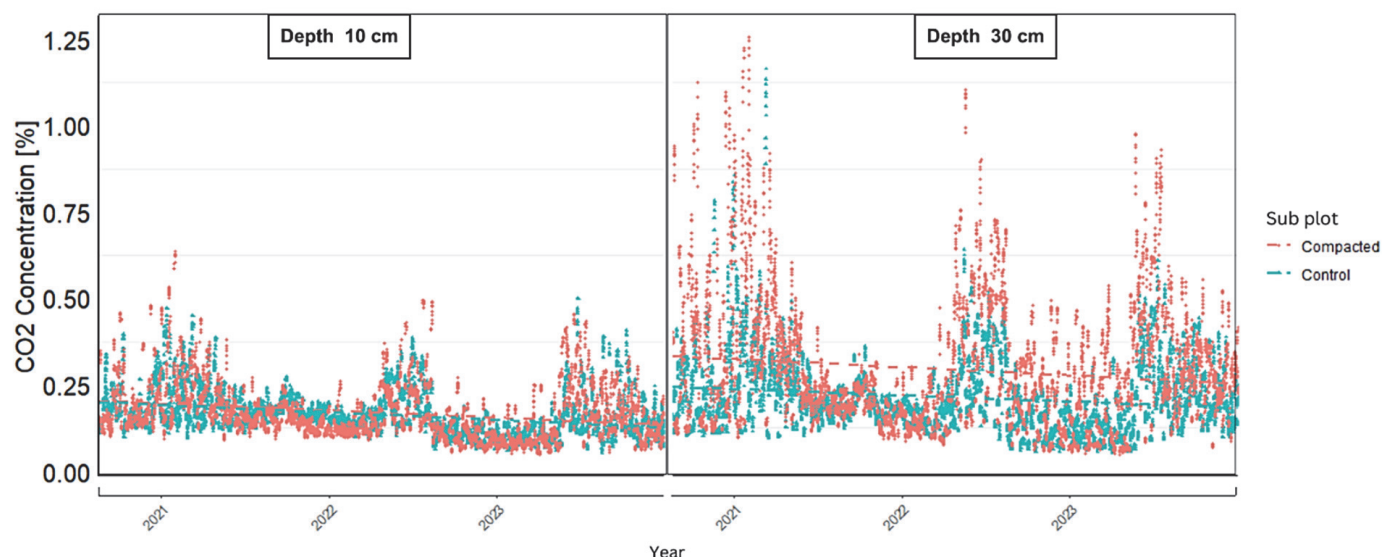


Figure 7. Variability of CO₂ concentration measurements at soil depths of 10 cm and 30 cm across sub-plots, including trend lines (dashed) that indicate the long-term development of the CO₂ concentration in soil.

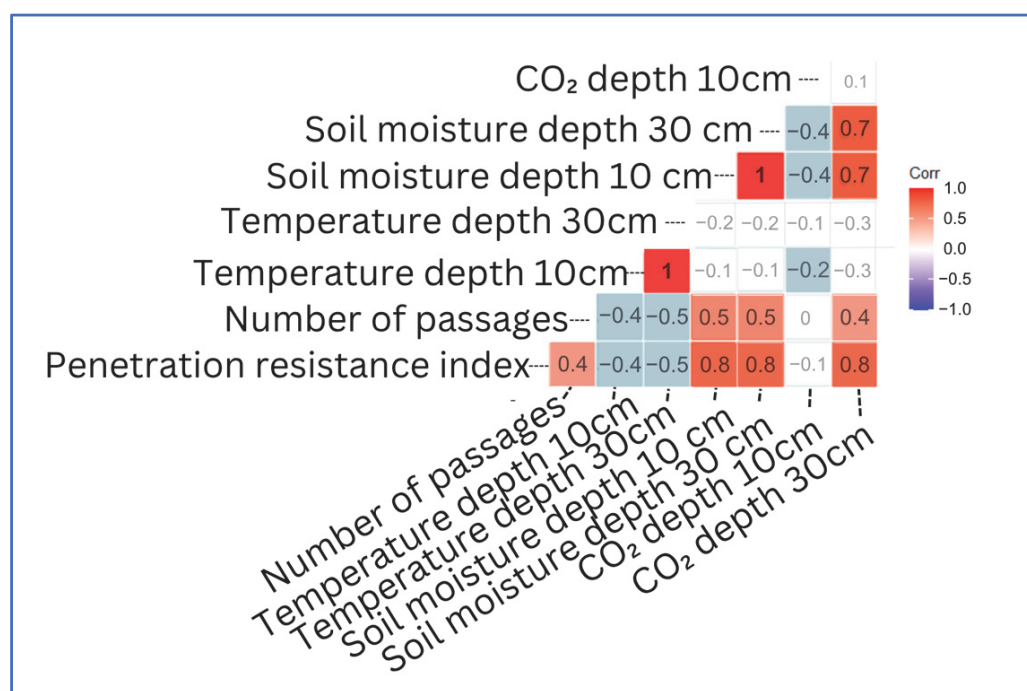


Figure 8. The correlation matrix between key variables. The values represent Spearman's correlation coefficient (significant correlations indicated by color and non-significant correlations left uncolored).

During the temperature measurements (Figure 10), the control sub-plot consistently exhibited higher soil temperatures. Over the 3-year period, the average temperature at the control sub-plot was 0.20 °C (+3%) higher at 10 cm depth and 0.21 °C (+3%) higher at 30 cm depth. The most pronounced temperature differences occurred in spring, at the onset of the growing season, with the largest discrepancy at 10 cm (+0.61 °C) recorded on 13 April 2023 and at 30 cm (+0.76 °C) on 21 April 2022. Seasonal analyses revealed that mean temperature differences at 10 cm between the control and the compacted sub-plot were +0.45 °C in spring (March, April, and May), +0.14 °C in summer (June, July, and August), +0.14 °C in autumn (September, October, and November), and +0.03 °C in winter

(December, January, and February). At 30 cm, the differences were $+0.46$ °C in spring, $+0.18$ °C in summer, $+0.12$ °C in autumn, and $+0.03$ °C in winter. These temperature differences between sub-plots were statistically significant ($p < 0.05$), except on 1 February 2023. Temperature variability was found to be highest in autumn and spring, with SD (standard deviation) values ranging from 3.5 to 3.7 °C at both depths. These increased fluctuations can be attributed to transient seasonal conditions when changes between cooler and warmer temperatures are more frequent. Conversely, winter and summer showed the lowest temperature variability (1.3 – 1.9 °C), indicating greater temperature stability during these periods of more stable atmospheric conditions.

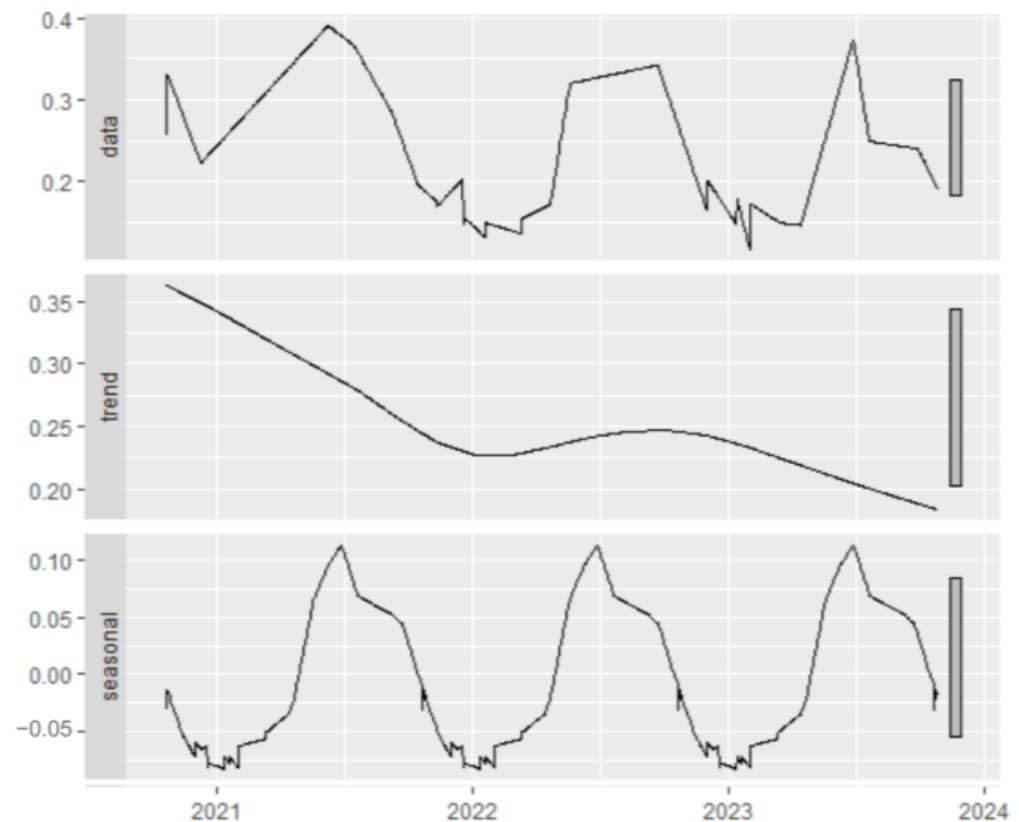


Figure 9. Seasonal-Trend Decomposition (STL) of CO₂ concentrations at the compacted plot using Loess over a three-year period following compaction.

Soil moisture measurements (Figure 11) showed greater differences between sub-plots than those observed for soil temperature, with the most substantial differences occurring in winter and spring. At the control sub-plot, soil moisture was on average -7.77% (-15%) lower at 10 cm depth and -7.92% (-16%) lower at 30 cm depth than at the compacted soil. The greatest differences in soil moisture at 10 and 30 cm soil depth of -25.20% and -25.45% , respectively, were recorded on 1 February 2023. Seasonal comparisons of soil moisture revealed differences at 10 cm depth of -7.06% in spring, -5.60% in summer, -5.00% in autumn, and -8.98% in winter. At 30 cm, the differences were -11.29% in spring, -6.34% in summer, -5.99% in autumn, and -10.6% in winter.

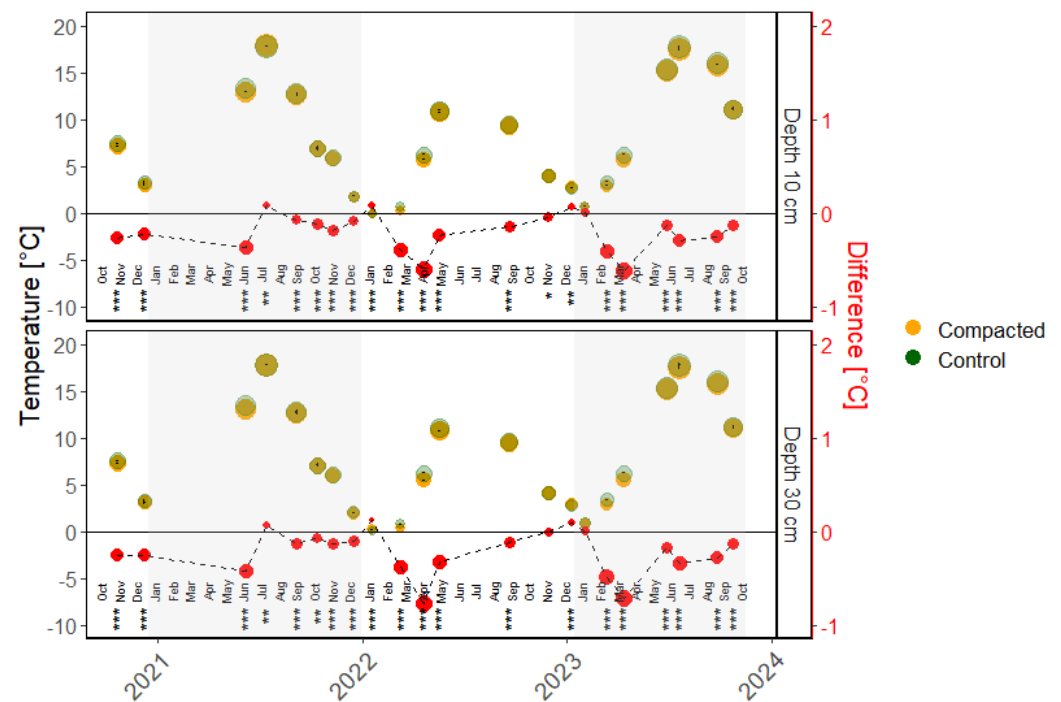


Figure 10. Comparison of mean temperature at the control (green) and compacted (orange) sub-plot, including the differences (red) at depths of 10 cm and 30 cm. The size of each point represents the temperature value, while the black vertical lines within points represent 95% confidence intervals of the mean and indicate measurement variability. Significant differences between the sub-plots are indicated as follows: 0.001 '****', 0.01 '***', 0.05 '**'.

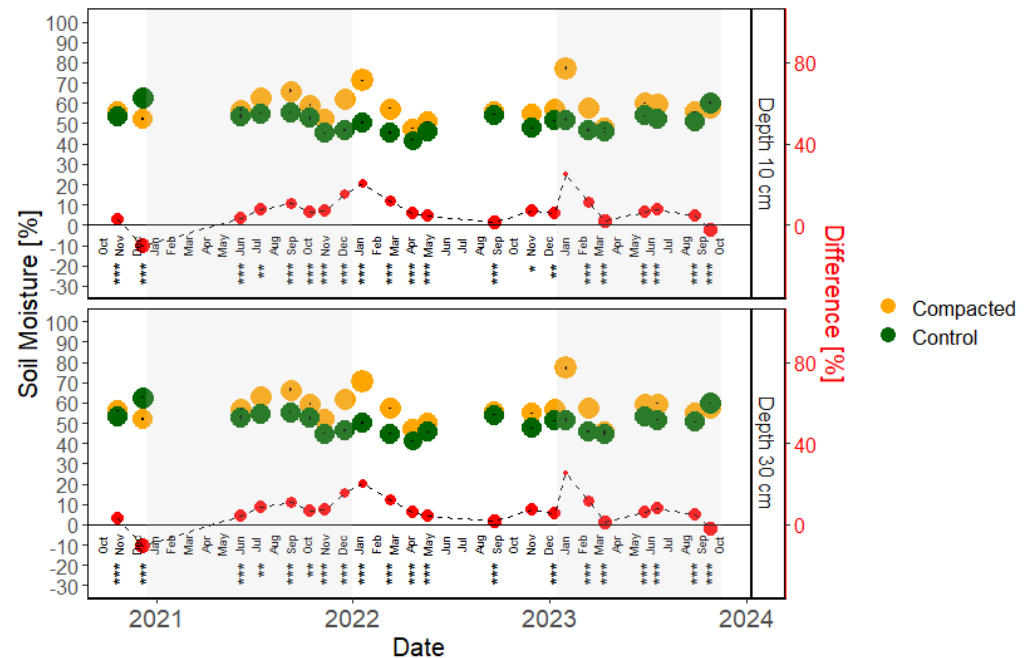


Figure 11. Comparison of mean soil moisture at the control (green) and compacted (orange) sub-plots, including the differences (red) at depths of 10 cm and 30 cm. The size of each point represents the soil moisture, while the black vertical lines within points represent 95% confidence intervals of the mean and indicate measurement variability. Significant differences between the sub-plots are indicated as follows: 0.001 '****', 0.01 '***', 0.05 '**'.

4. Discussion

Our study demonstrated that tractor traffic caused significant changes in soil physical properties, particularly in the form of increased compaction. This mechanical disturbance led to changes in soil gas exchange dynamics, soil temperature, and moisture regime. A partial recovery of CO₂ levels was observed at 10 cm depth over the two years, but this recovery was not evident at greater depths. At 30 cm depth, there was a statistically significant difference in CO₂ concentration between the control and compacted sub-plots throughout the measurement period.

4.1. Soil Compaction

This study revealed significantly increased values of penetration resistance, as indicated by the penetration index. Following the compaction treatment, penetration resistance values were elevated by an average of 19% at the 0–10 cm soil depth, reaching the maximum increase of 34% at the 3 cm depth. These findings align with broader evidence that mechanized operations influence surface and soil structure [7,11,18,23], thereby influencing penetration resistance [24]. However, Kormanek et al. [25] reported a limited impact of machine traffic. This contrast may be attributed to the protective effect of the surface organic layer and the use of low ground-pressure machinery [9,26]. The increase in penetration resistance was strongly correlated with elevated CO₂ concentrations at the depth of 30 cm ($r = 0.8$), suggesting that reduced soil porosity—resulting from compaction—limited gas diffusion and contributed to CO₂ accumulation in deeper soil layers. These findings align with Feng et al. [4], who reported that compaction reduces soil gas permeability by 63%–93%. Similar conclusions were reached by Kim et al. [14], who observed significant increases in soil CO₂ concentrations in compacted soils, especially during the growing season.

4.2. Soil CO₂ Concentrations

Over the three-year period following the compaction treatment, average soil CO₂ concentrations were consistently and significantly higher in the compacted sub-plot compared to the control. At a depth of 30 cm, 21 out of 22 measurements showed statistically significant differences ($p < 0.05$), while at a depth of 10 cm, significant differences were observed in 13 out of 22 measurements. ($p < 0.05$). The average CO₂ concentration in the compacted sub-plot was 0.293% at a depth of 30 cm and 0.169% at 10 cm. In comparison, the control sub-plot recorded average concentrations of 0.214% at 30 cm and 0.163% at 10 cm. These results also confirm that CO₂ concentrations were generally higher at greater soil depths and are consistent with findings from previous studies, which have shown that CO₂ concentrations tend to increase with depth due to reduced diffusion rates, greater microbial activity, and root respiration in deeper soil layers [12,27]. Moreover, it has been reported that CO₂ concentrations in the organic horizon are typically only slightly above atmospheric levels (e.g., around 0.04%), whereas concentrations increase significantly in the mineral layers below [3,28]. The analysis of our data clearly showed that soil CO₂ concentrations increased with compaction treatment. Allman et al. [29] reported that forestry machine traffic significantly affects CO₂ concentration in soils. Critical concentration of CO₂ fluctuates around 0.6%, and exceeding this threshold can result in reduced root growth in seedlings [30–32]. In our study, the mean CO₂ concentrations in compacted sub-plots remained well below this critical threshold across all years and depths. At 30 cm depth, average concentrations in the compacted sub-plot declined from 0.348% in the first year post-compaction to 0.265% and 0.267% in the second and third years, respectively. Similarly, at 10 cm depth, values decreased from 0.203% to 0.143% over the same period. Although compaction clearly elevated CO₂ levels relative to control sub-plots—where mean concen-

trations ranged from 0.246% to 0.186% at 30 cm and from 0.188% to 0.130% at 10 cm—these levels remained below the 0.6% threshold associated with physiological stress in plant roots. These findings suggest that while compaction can significantly affect gas dynamics in forest soils, the observed concentrations may not reach levels considered critical for root function, particularly in the context of moderately compacted soils.

4.3. Seasonal Trend in CO₂ Concentrations

A distinct seasonal pattern in soil CO₂ concentration was observed, with higher values at 30 cm depth during the growing season (April to September) and lower, less variable concentrations in winter (December to February). Sub-plot differences were more pronounced during the growing season and diminished in winter. STL decomposition further confirmed this seasonal trend, showing clear peaks during the growing season and a consistent decline in CO₂ concentration over the three years post-compaction, as indicated by the trend component (Figure 9). Similar seasonal trends have been documented in other studies. For instance, studies in European beech and Scots pine stands reported CO₂ concentration minima in winter and peaks in summer, closely associated with changes in soil temperature and moisture [33]. In a Finnish Scots pine forest, soil CO₂ efflux varied seasonally, with higher rates in late summer compared to spring at equivalent soil temperatures, indicating the influence of biological activity such as root and microbial respiration [34]. Consistent with prior findings [3], our data showed lower CO₂ concentrations at 10 cm compared to 30 cm depth, with both depths exhibiting seasonal fluctuations. Kim et al. [14] also reported higher soil CO₂ concentrations primarily during the growing season, with reduced variability and negligible differences during winter. Similarly, the highest concentrations were typically observed in late summer (August–September), while the lowest occurred in winter (December–February) [1].

4.4. Temperature and Soil Moisture Regimes

Soil moisture measurements revealed pronounced differences between compacted and control sub-plots, particularly during winter and spring, with the most substantial deviation recorded on 1 February 2023—25.2% at 10 cm and 25.45% at 30 cm depth (Figure 11). On average, soil moisture at the control sub-plot was 7.77% lower at 10 cm and 7.92% lower at 30 cm compared to the compacted sub-plot, with seasonal contrasts most evident in spring and winter. Higher soil moisture in the compacted sub-plot suggests slower water infiltration and reduced hydraulic conductivity, likely due to compaction, which also affects the soil's water regime and temperature. The increased soil moisture on the compacted sub-plot contributes to lower soil temperatures, likely due to reduced permeability of the upper soil layers and increased water retention. The results of another study show that compaction slows water percolation by reducing soil pore space, potentially leading to surface runoff [35]. However, given that the study area is situated on a gentle slope (<5%), surface runoff is unlikely. Instead, the elevated moisture content is more plausibly attributed to localized waterlogging caused by restricted drainage in compacted soils. Soil compaction during mechanized logging reduces macropores in the soil [36], thereby decreasing water infiltration [37] and increasing the potential for soil erosion on steeper slopes [38]. On flat or mildly sloped areas, compaction leads to slower water infiltration and waterlogging [39]. In our study, reduced soil porosity and infiltration in the compacted sub-plot led to an average increase of 15% in soil moisture, likely due to enhanced surface water retention and slower drainage. The maximum observed difference of +25% on 1 February 2023 indicates the potential for prolonged waterlogging or inefficient water redistribution in the compacted areas. With an increasing number of machinery passes, the infiltration rate further declines. The most significant change occurs after the initial passes,

when the infiltration rate can drop by up to 50% [37]. A moderate positive correlation ($r = 0.5$) between soil moisture and the number of machine passages, along with a strong positive correlation ($r = 0.8$) between soil moisture and the penetration resistance index—a proxy for soil compaction—suggests that compaction increased soil moisture content by reducing soil permeability and impeding water infiltration. Barik et al. [40] obtained similar results in their study, where they measured soil moisture content up to a depth of 30 cm. After compaction, soil moisture increased on average by 12.7%. Significant differences in soil moisture following compaction were also reported in other studies [41–43]. Hydraulic conductivity is a highly sensitive indicator of soil compaction. Compared to bulk density and reduced soil porosity, hydraulic conductivity exhibited the most significant change in 67 studies focusing on soil compaction and its effects on soil characteristics [23]. The primary cause of the large reduction in hydraulic conductivity is the decrease in macropores, which play a critical role in water infiltration into the soil [44].

4.5. Recovery of Soil

In our study, even two years after the passage of forestry machinery, higher CO₂ concentrations were measured at a depth of 30 cm. Unlike the 10 cm depth, where CO₂ concentration in the compacted sub-plot stabilized at levels comparable to the control sub-plot, the CO₂ concentration at 30 cm depth at the compacted sub-plot did not reach the control level even after two years. However, we observed a declining trend in CO₂ concentration at this depth, indicating a possible recovery (Figure 9). Further long-term monitoring is necessary to estimate the timeline for soil recovery after compaction, particularly in deeper soil horizons. The recovery time of soil following compaction can vary widely, from as short as one year [15] to as long as 20 years [16], depending on the parameter used to assess the recovery and also on soil characteristics [17], environmental conditions [18], and duration and intensity of machinery impact [45,46]. According to Labelle [47], soil recovery can take between 5 and 30 years.

5. Conclusions

This study highlights the significant impact of forest machinery operation on soil compaction and the associated effects on soil properties and CO₂ dynamics. The results confirmed that soil compaction increased penetration resistance, with values increasing on average by 19% (0–10 cm depth) and reaching a maximum of 34% (3 cm depth).

Our findings show that CO₂ concentrations in compacted soils remained elevated two years after machinery passage, especially in deeper layers. At a depth of 10 cm, CO₂ concentrations reached the levels comparable to the control plot within two years, indicating partial recovery in the topsoil. However, deeper layers showed slower recovery, with CO₂ levels at 30 cm still significantly higher at the compacted sub-plot. Seasonal variability in CO₂ concentration was also evident, with the highest values observed during the growing season due to reduced permeability in the compacted soil layer and increased autotrophic respiration by root systems and rhizosphere microorganisms.

These results are consistent with previous studies showing that soil compaction reduces hydraulic conductivity, air permeability, and porosity, thereby limiting gas exchange and water infiltration while increasing moisture retention. The reduced permeability of compacted soils creates conditions that inhibit the diffusion of CO₂ and lead to its accumulation beneath the compacted layer. This phenomenon is exacerbated during the growing season when biological activity peaks, while differences between sub-plots are less pronounced during winter months.

Considering these findings, forest management should prioritize minimizing soil compaction to protect soil structure and function. The most effective mitigation strategy

involves restricting forest machinery movements to designated skid trails and avoiding uncontrolled traffic through forest stands. Long-term monitoring is essential to better understand the timing of restoration of deeper soil horizons and to develop sustainable silvicultural practices that maintain soil health and ecosystem function. Thanks to the three-year duration of the experiment, we were able to investigate the dynamics of soil characteristics, including temperature, moisture, and CO₂ concentration, as well as their temporal development following the soil compaction event.

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