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Changes in the concentration of CO_2 in forest soils resulting from the traffic of logging machines

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Abstract: The aim of the study was to find out whether and how the forest soil compaction resulting from the traffic of forest logging machines results in the increased soil air concentration of CO_2, occurring over a longer period of time and in different seasons of the year. Changes in the soil air CO_2 concentrations were monitored in two periods: in winter (cold period) and in summer (warm period). CO_2 concentrations were measured in compacted and non-compacted soil using a certified measurement. In addition to the soil concentration of CO_2, air temperature, soil temperature and soil moisture content were measured. The research was conducted in the Czech Republic. The obtained data was subjected to statistical analyses (Student's t-test; correlation analysis). The results of the study confirm the long-term influence of soil compaction by the traffic of forest machinery on the CO_2 concentration in soil in both seasons (cold and warm). The concentration of CO_2 in the air of compacted soil was always significantly higher in both periods than the CO_2 concentration in the air of non-compacted soil (control). Thus, the negative influence of soil compaction was clearly demonstrated as a result of a single pass of forestry machines over the soil surface.

Keywords: carbon dioxide; compacted soil; forest ecosystems; soil disturbance; soil moisture; soil temperature

Management procedures of forest regeneration and harvesting frequently require the use of heavy machines, often not taking into consideration the potential risk of soil compaction (Cambi et al. 2015) and its distribution in the soil profile (Nazari et al. 2021). Forest machines used in forest logging are generally very heavy and can cause considerable damage to the forest soil, whose bearing capacity is often very poor (Poltorak et al. 2018). This shows especially after repeated traffic of machines, which results in soil compaction and the formation of ruts. Thus, soil porosity is impaired and soil density increases (Cambi et al. 2015; D'Acqui et al. 2020). Moreover, there is a permanent trend in forest harvesting to continuously increase the size, output and loading capacity of logging machines with weight which is in general 12–16 t (unladen state) (Ampoorter et al. 2007), this being given by the fact that juvenile thinning and logging are performed by harvesters and forwarders in most industrially advanced countries. The use of heavy forest machines has significantly increased in the last decades (Cambi et al. 2015). Nevertheless, mechanisation of forest operations

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in forest harvesting is inevitable as it brings benefits of reducing costs, manual work and efficient wood production.

Forest machines moving across the forest soil often cause destruction of soil structure, structural changes (Greacen, Sands 1980), soil surface deformation, erosion (Cambi et al. 2015) and increased soil density. The growing use of heavy machines increases soil stress to greater depths, and this is why the heavy compaction of forest subsoil is reported as compared with the past (Keller et al. 2019). Moreover, the heterogeneous structure of machine traffic across the forest stand increases physical disturbance to the soil surface, which may also affect the lower soil layers (Nazari et al. 2021). These changes in the physical properties of soils increase bulk weight and resistance to the penetration of growing roots, decreasing macroporosity, water infiltration and airflow (Cambi et al. 2017). Heavy forest machines also cause soil physical degradation, which results in changes in the chemical and biological properties of the soil (Horn et al. 2007).

Forest machines initiate the soil compaction due to normal pressure, vibrations and shear stress (Kozlowski 2000). The traffic of these machines induces a real pressure on the soil surface, which is affected primarily by tyre characteristics in wheeled machines (such as diameter, width, stiffness and degree of tyre inflation) and stability of the machine (Mergl, Kašpárek 2022). Other important parameters include tyre adhesion and load, and components of traction forces acting on the wheel (Zemánek, Neruda 2021). The contact area between drive tyres and the soil and their basic dimensions affect the traction characteristics of machines and changes in the soil physical parameters (Bekker 1956). In addition, soil compaction is significantly affected by the operating parameters of tyres, wheel slip, travel speed and number of passes (Marsili, Servadio 1996).

Soil compaction is a form of physical degradation of soil which causes its compaction, bringing the soil particles closer together, or reduced porosity and impaired soil permeability, which results in the increased bulk weight of dry soil (Veronesi et al. 2012; Lee et al. 2020) and is a consequence of pressure developed on the soil by tyres or machine tracks. Due to soil compaction, forest machines and their intensive operations in forests increase the risk of soil physical degradation, which can significantly impair soil productivity and all functions of the ecosystem (Gaertig et al. 2002). Soil compaction contributes to soil erosion and reduced soil porosity, decreased water infiltration and soil aeration (Hamza, Anderson 2005; Riggert et al. 2016). Soil compaction also causes changes in the soil structure, an increase in bulk weight and a decrease in soil macroporosity and interconnection between the pores (Nawaz 2012). Moreover, the intensive traffic of machines across the forest stand creates furrows generating complex microtopography with a succession of mounds and hollows and local differences in soil porosity, all of this affecting water circulation, soil water content, porosity filled with air (Cambi et al. 2015) and change in the concentration of carbon dioxide.

In a settled state, the production of CO_2 in the soil is a result of the breathing of roots and decomposition of soil organic matter (Epron 2009), often referred to as autotrophic and heterotrophic sources (Subke et al. 2006). The effect of soil compaction on roots or the metabolism of microbes also affects the release of CO_2 from the soil. Similarly, changes in soil physical properties that alter gas diffusion will modify the relation between the release of CO_2 from the soil and the soil concentration of CO_2 (Epron 2009). The intensive traffic of machines in the forest stand will change the composition of soil atmosphere and the release of soil gases, CO_2 in particular (Ball et al. 1999). It follows that, apart from some exceptions (Ponder et al. 2005), the release of CO_2 from the soil is negatively affected by soil compaction (Goutal et al. 2012; Hartmann et al. 2014).

It is known that changes in CO_2 concentration following after the soil compaction are shown almost immediately by its increase and this increased concentration settles within a relatively short time of several hours at a value which persists and is markedly higher as compared with soil air CO_2 concentrations on the control site with undisturbed soil (Gebauer, Martinková 2005). However, no data is available on how long these increased CO_2 concentrations persist and whether and how their values change in relation to site climatic conditions (cold or warm season of the year). The aim of the present study was therefore to find out whether and how the consequences of forest soil compaction, caused by the traffic of heavy machines and showing in the increased concentration of CO_2 in soil air, occur and change over a longer time period and in different seasons of the year. The main

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hypothesis (H_1) is that levels of CO_2 concentration in the soil compacted by the heavy machine traffic will be significantly different from CO_2 concentrations in the natural non-compacted soil, and that the differences will be demonstrated over a long term, both in the cold and warm periods of the year. At the same time, an assumption was made that, in addition to the soil compaction by the traffic of heavy machines, the increased CO_2 concentrations will depend on some other factors such as air temperature (t_v), soil temperature (t_p) or relative soil moisture content (ρ).

MATERIAL AND METHODS

Changes in the concentration of CO_2 in soil air were studied during two seasons of the year for approximately thirty days, once in winter (cold) and once in summer (warm). In addition, air temperature, soil temperature and soil moisture content were measured. The data obtained were then subjected to standard statistical analyses, testing mainly the difference between CO_2 concentrations in the compacted and non-compacted soil and the significance of some external factors for the degree of CO_2 concentration in the soil. The aim of this research was also to verify the assumption that an increased CO_2 concentration in the soil air persists for a much longer time than only hours or days after soil compaction and that it is also affected by some external factors such as air temperature, soil temperature and soil water content.

The system measuring the CO_2 concentration automatically recorded values continually at the selected hour interval at a soil depth of 12 cm. A depth of 12 cm was chosen to detect the soil values in the layer most affected by the machine tyres. The CO_2 concentration was measured using the instrumental chain made by Vaisala (Finland), consisting of the measuring instrument CARBOCAP GSM 70 with two connected measuring probes CARBOCAP GMP 221. This instrument was applied to the soil with a hand-held hollow auger. This auger was sized to match the diameter of the probe. The basic range of measuring the CO_2 concentration by the probes was up to 5% with an accuracy of 0.02%.

The GMP 221 probes enable the measurement of the instantaneous concentration of CO_2 and the recording of the measured values at chosen intervals. In our study, we selected an interval of 60 minutes, i.e. once an hour. Inside the lower part of the probe body, there is an infrared CO_2 sensor covered with a grid and membrane. Holes in the grid let the air into the sensor, protecting the sensor against pollution at the same time. The probes are based on the principle of measuring the absorption of infrared rays in CO_2 contained in the air. The cylindrical probe is 95 mm long, and its diameter is 18.5 mm. A cable connects the upper part of the probe body to the GSM 70 instrument. One or two probes (which were used in our study) can be connected to the GMP 221 – the instrument was measuring and recording the CO_2 concentration data on two sites: in compacted and non-compacted soil.

For the research purposes, the measuring probe was equipped with a plastic tube case 30 mm in diameter and 12 cm in length, whose upper side was provided with a ring 7 mm wide. The tube case was to reinforce the wall of the hole into which the probe is inserted. A system of holes was drilled in the lower half of the case wall, allowing the passage of soil air into the case from the soil in which the case with the probe is installed. Soil air gets into the inner space of the case also through its open lower end. The case is sealed in the upper part with a rubber stopper with a hole in which the measuring probe is inserted. The case was inserted into a calibrated hole in the topsoil layer to a depth of ca. 14 cm. It prevented the walls of the hole with the inserted probe from potential collapse, still allowing soil air to get into the vacant space of the case. To obtain data on CO_2 concentrations in compacted and non-compacted soil, one case with the probe was always inserted into the compacted soil (values of CO_2 concentrations in the compacted soil – hereinafter the data file CO_2-I), and the other case with the probe was inserted into the non-compacted soil as a control (values of CO_2 concentrations in the non-compacted soil – hereinafter the data file CO_2-II) (Figure 1).

Air and soil temperatures were measured using common methods with the electronic pen-type thermometer DT-131 (measurement accuracy 1.5%, pen-type probe of 12 cm in length) (Delta-T Devices Ltd, United Kingdom). Relative soil moisture ρ (%) was measured with the electronic soil moisture meter Delta-T HH2 with the pen-type four-point probe (Delta-T Devices Ltd, United Kingdom).

Experimental plots. Research data was collected in the Vranov cadastral area, Czech Republic. The terrain relief of the experimental site

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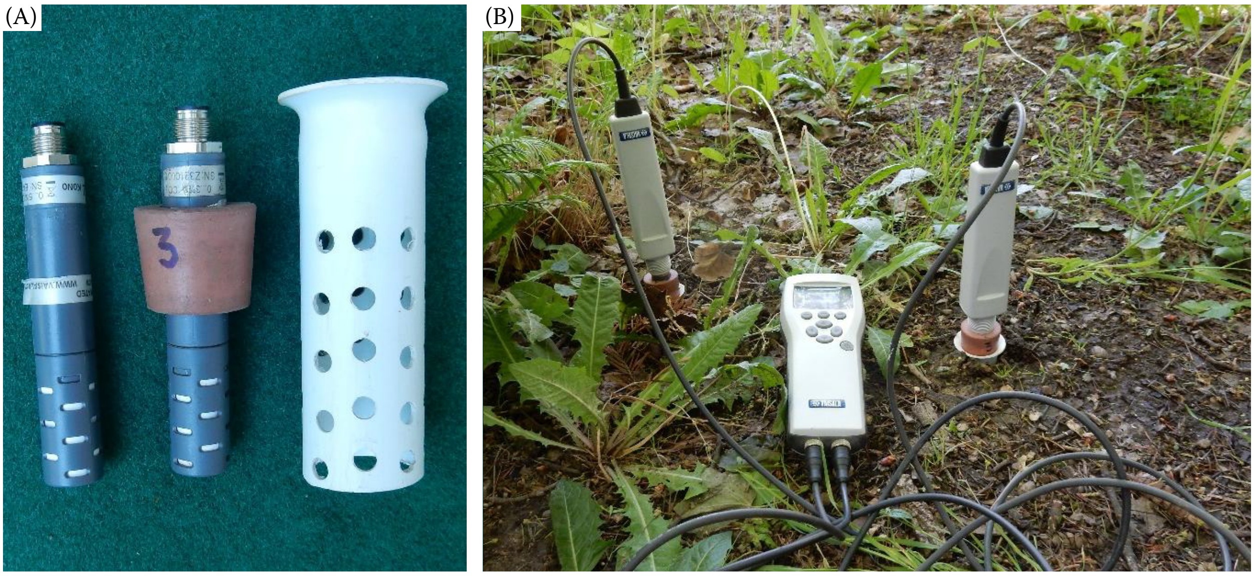

Figure 1. The system measuring CO_2 concentrations in the soil air: (A) GMP 221 probe, GMP 221 probe with a rubber stopper, and a case for probe insertion into the soil; (B) arrangement of the measuring system (the instrument CARBOCAP GSM 70 with two connected GMP 221 probes inserted in cases into the soil)

is flat. The main tree species represented on the site was beech (*Fagus sylvatica*; 80%). The remainder was composed of spruce (*Picea abies*; 20%). The trees are 50 years old. The choice of the experimental site was based on the soil characteristics of the site, age and forest tree species.

The degree of soil compaction on the experimental plot corresponded to the state of the soil in the rut formed after one passage of a heavy machine, a 6-wheeled harvester. This machine weighs 24.3 t. The front tyre size is 650×26.5' and the rear tyre size is 650×34'. The degree of soil compaction in the ruts of wheels after the machine traffic was expressed only indirectly by the depth of the pressed-out track of wheels and by the change in penetration resistance at ca. 10–15 cm under the soil surface, measured with a mechanical penetrometer (Eijkelkamp, Netherlands). The depth of the rut bottom ranged from 6 cm to 8 cm, and the penetration resistance on non-compacted and compacted soil was 0.7 MPa and 0.9 MPa, respectively. The soil compaction corresponded intentionally to values caused by only one passage of a heavy machine, i.e. to the situation which is usually considered unimportant and causing no damage to the forest soil in forestry practice.

The experimental plot with the compacted soil into which Probe 1 was inserted as described above was about 1 m distant from the control plot with the non-compacted soil into which Probe 2 was inserted. This is how the homogeneity of soil characteristics was achieved on the two plots. Soil within the experimental plots had a medium loam to sand texture. Measurements in the winter (cold) period were taken from January 14, 2023, to February 13, 2023, and measurements in the summer (warm) period were done from July 6, 2023, to August 7, 2023. The time interval for the automatic reading of CO_2 concentration values was 60 min, soil temperatures and moisture were measured manually, always at 6:00 a.m. and 3:00 p.m.

Data processing. The obtained data were subjected to standard statistical tests, among others also to the assessment of CO_2 concentration similarity in the soil air of compacted and non-compacted soil (Student's t-test), and evaluation of the extent to which the CO_2-I and CO_2-II content depends on air temperature t_v, soil temperature t_p, and relative soil moisture content ρ (correlation analysis).

The evaluation of the pattern of measured data in the two seasons of the year and results of statistical surveys are reflected in conclusions about the formulated hypotheses.

RESULTS

Results of measuring CO_2 content in the cold season of the year. Figure 2 presents records from the measuring of CO_2 content in the cold period in the compacted soil (CO_2-I; %) and in the non-

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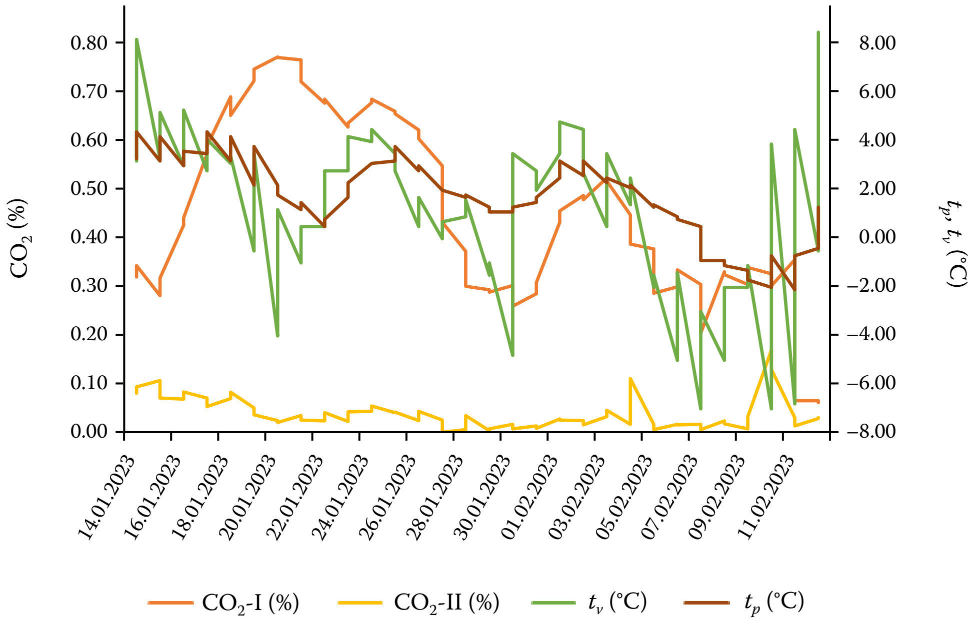

Figure 2. Diagram of the CO_2 concentrations in soil air and levels of air temperature t_v and soil temperature t_p in the cold period from January 14 to February 12, 2023

compacted soil (CO_2-II; %). Moreover, the courses of air temperatures t_v (°C) and soil temperatures t_p (°C) are presented. All measured characteristics were recorded in time. Figure 2 shows that the CO_2 concentrations significantly differ between CO_2-I and CO_2-II and that the values of CO_2 concentrations in the data file CO_2-I are markedly higher than the values of CO_2 concentrations in the data file CO_2-II.

The parameter 'Assessment of the similarity of CO_2 in the soil air of compacted and non-compacted soil' was to find out whether the CO_2 concentrations in CO_2-I and CO_2-II were similar or not. Assessing these concentrations (see the diagram in Figure 2) and the statistical evaluation (Table 1), a significant difference was clearly demonstrated between the two data files CO_2-I and CO_2-II. CO_2 concentrations in CO_2-I (compacted soil) are significantly higher than the data in CO_2-II (non-compacted soil). Based on this fact, it can be stated that the effect of soil compaction on the increased content of CO_2 in the soil air was demonstrated.

Another subject of research was to assess the degree of correlation between the CO_2 concentration in the data file CO_2-I and air temperature t_v. Results of the statistical assessment showed (Table 1) that the value of the correlation coefficient was only slightly different from zero, and that the dependence of variable y on variable x was very low, and thus, the correlation relationship did not exist. Therefore, it can be stated that in the data file CO_2-I, the CO_2 content is not dependent on air temperature t_v (Figure 3).

Results of the statistical assessment showed (Table 1) that the value of correlation coefficient significantly differed from zero and that the dependence of variable y on variable x was relatively strong; thus, the correlation relationship was existing. Therefore, it can be stated that the CO_2 concentration in CO_2-I depends on soil temperature t_p (Figure 4).

A further subject of research was to assess the degree of correlation between the CO_2 concentration in the data file CO_2-I and relative soil moisture content ρ. Results of the statistical assessment showed (Table 1) that the value of the correlation coefficient differed only very little from zero and that the dependence of variable y on variable x was very low; thus, there was no correlation relationship. Therefore, it can be stated that in the data file CO_2-I, the content of CO_2 was not dependent on the relative soil moisture content ρ (Figure 5).

A further subject of research was to assess the degree of correlation between the CO_2 concentration in the data file CO_2-II and air temperature t_v. Results of the statistical assessment showed (Table 1) that the value of the correlation coefficient differed only very

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Table 1. Statistical assessment of the dependence of CO_2 content in the soil air on some factors in the period from January 14, 2023, to February 13, 2023

Parameter	Calculated value of decisive quantity	Critical values of decisive quantity	Relation between the calculated and critical values of decisive quantity	Final evaluation
Assessment of similarity in the soil air CO_2 content of compacted and non-compacted soil – data files CO_2-I and CO_2-II	16.711	$t_{0.25} = 1.960$ $t_{0.005} = 2.576$	$t\ (16.711) > t_{0.025}\ (1.960)$ $t\ (16.711) > t_{0.005}\ (2.576)$	statistically significant difference between CO_2-I and CO_2-II, the effect of soil compaction on increased CO_2 content was conclusively demonstrated
Assessment of the degree of dependence of CO_2 content in CO_2-I on air temperature t_v	0.136	$r_5 = 0.2546$ $r_1 = 0.3306$	$r\ (0.136) < r_5\ (0.2546)$ $r\ (0.136) < r_1\ (0.3306)$	no statistical dependence, CO_2 content does not depend on air temperature t_v
Assessment of the degree of dependence of CO_2 content in CO_2-I on soil temperature t_p	0.470	$r_5 = 0.2546$ $r_1 = 0.3306$	$r\ (0.470) > r_5\ (0.2546)$ $r\ (0.470) > r_1\ (0.3306)$	statistical dependence exists, CO_2 content depends on soil temperature t_p
Assessment of the degree of dependence of CO_2 content in CO_2-I on relative soil moisture content ρ	0.129	$r_5 = 0.2546$ $r_1 = 0.3306$	$r\ (0.129) < r_5\ (0.2546)$ $r\ (0.129) < r_1\ (0.3306)$	no statistical dependence, CO_2 content does not depend on relative soil moisture content ρ
Assessment of the degree of dependence of CO_2 content in CO_2-II on air temperature t_v	0.234	$r_5 = 0.2546$ $r_1 = 0.3306$	$r\ (0.234) < r_5\ (0.2546)$ $r\ (0.234) < r_1\ (0.3306)$	no statistical dependence, CO_2 content does not depend on air temperature t_v
Assessment of the degree of dependence of CO_2 content in CO_2-II on soil temperature t_p	0.188	$r_5 = 0.2546$ $r_1 = 0.3306$	$r\ (0.188) < r_5\ (0.2546)$ $r\ (0.188) < r_1\ (0.3306)$	no statistical dependence, CO_2 content does not depend on soil temperature t_p
Assessment of the degree of dependence of CO_2 content in CO_2-II on relative soil moisture ρ	–0.058	$r_5 = 0.2546$ $r_1 = 0.3306$	$r\ (-0.058) < r_5\ (0.2546)$ $r\ (-0.058) < r_1\ (0.3306)$	no statistical dependence, CO_2 content does not depend on relative soil moisture ρ

CO_2-I – data file with the content of CO_2 in the soil air of compacted soil; CO_2-II – data file with the content of CO_2 in the soil air of non-compacted soil; t – temperature; r – correlation coefficient

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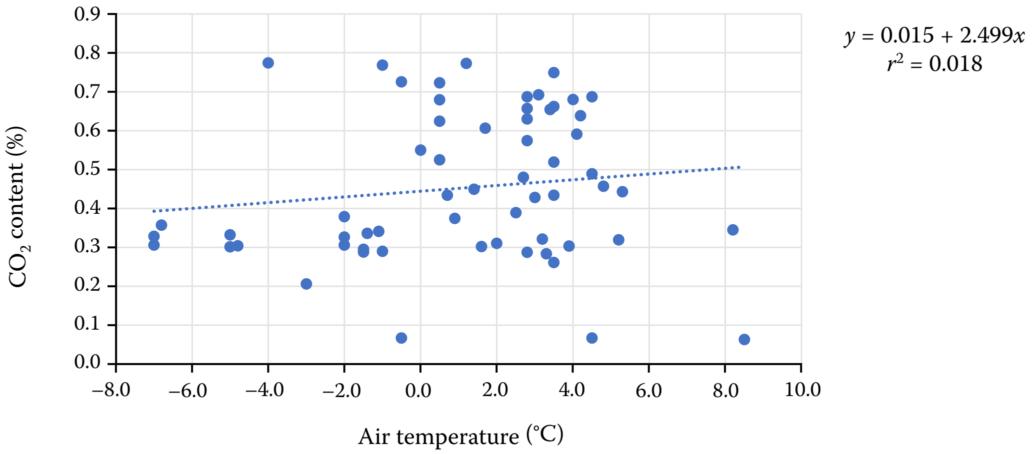

Figure 3. Dependence of CO_2 concentration on air temperature t_v in CO_2-I (cold season)

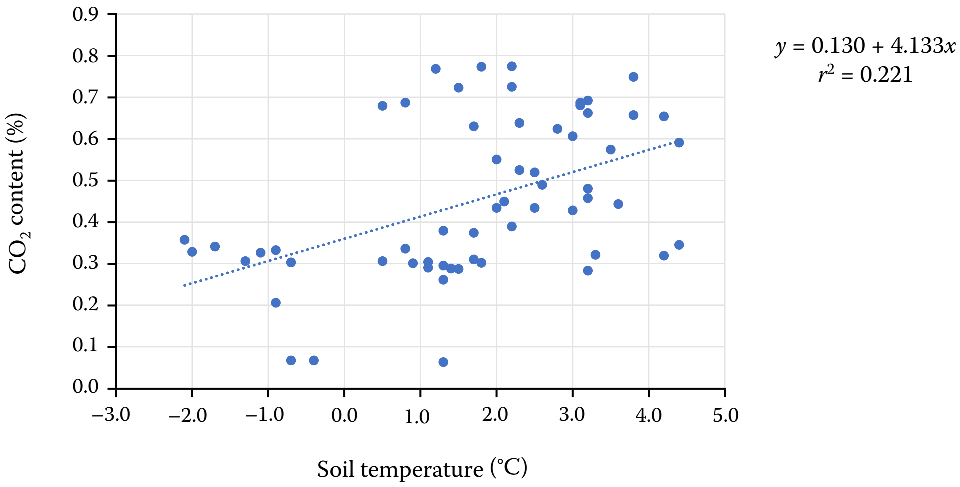

Figure 4. Dependence of CO_2 concentration in CO_2-I on soil temperature t_p (cold season)

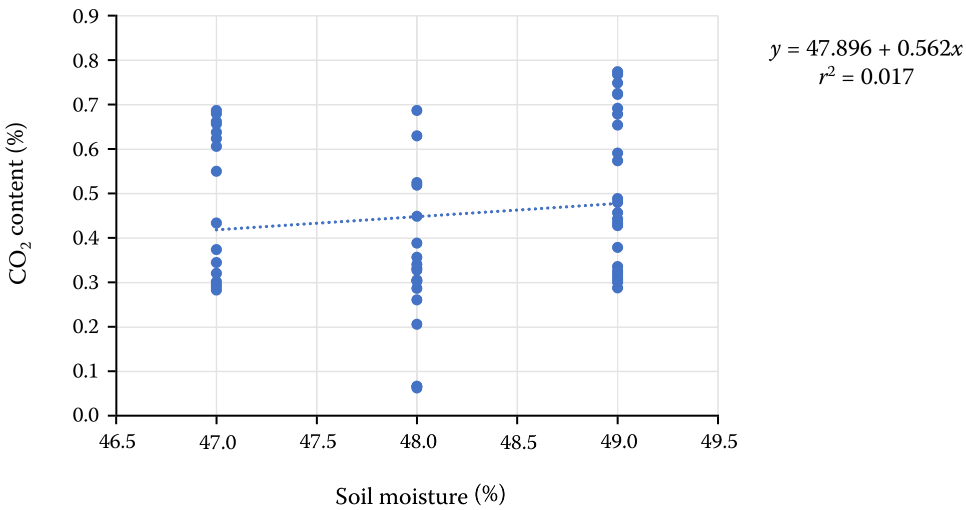

Figure 5. Dependence of CO_2 concentration in CO_2-I on relative soil moisture ρ (cold season)

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little from zero and that the dependence of variable *y* on variable *x* was very low; thus, there was no correlation relationship. Therefore, it can be stated that in the data file CO_2-II, the content of CO_2 was not dependent on air temperature t_v (Figure 6).

Another subject of research was to assess the degree of correlation between the CO_2 concentration in the data file CO_2-II and soil temperature t_p. Results of the statistical assessment showed (Table 1) that the value of the correlation coefficient significantly differed from zero and that the dependence of variable *y* on variable *x* was very low; thus, there was no correlation relationship. Therefore, it can be stated that in the data file CO_2-I the content of CO_2 was not dependent on soil temperature t_p (Figure 7).

Another research task was to assess the degree of correlation between the CO_2 concentration in the data file CO_2-II and relative soil moisture ρ. Results of the statistical assessment showed (Table 1) that the value of the correlation coefficient differed only very little from zero and that the dependence of variable *y* on variable *x* was very low; thus, there was no correlation relationship. Therefore, it can be stated that the CO_2 content in CO_2-II was not dependent on relative soil moisture ρ (Figure 8).

Results of CO_2 measurement in the warm season of the year. Figure 9 presents records from the measurement of CO_2 content in the soil in the compacted soil (CO_2-I; %) and in the non-compacted soil (CO_2-II; %), as well as the patterns of air temperature t_v (°C) and soil temperature t_p (°C). All meas-

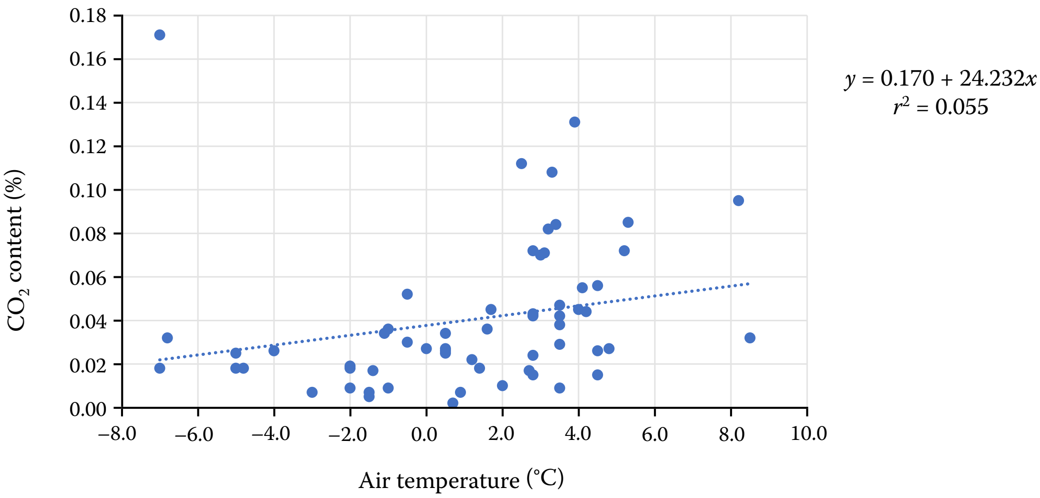

Figure 6. Dependence of CO_2 concentration in CO_2-II on air temperature t_v (cold season)

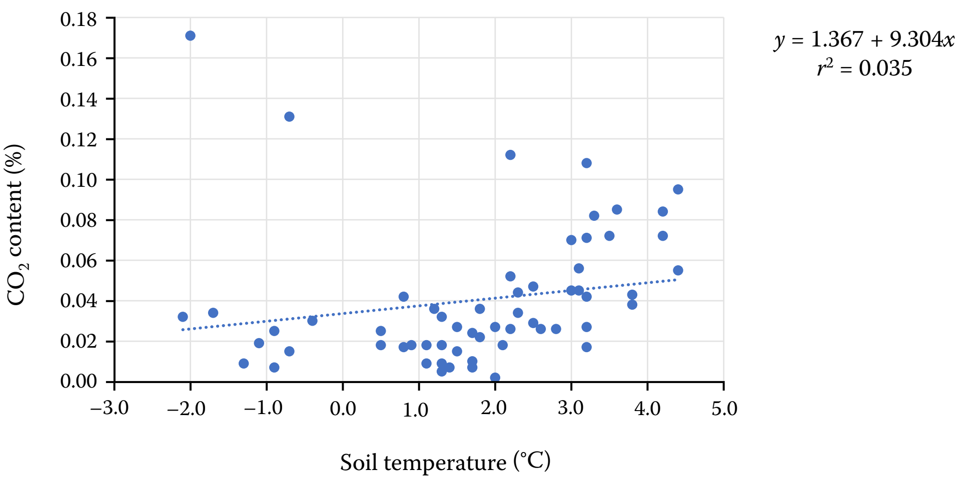

Figure 7. Dependence of CO_2 concentration in CO_2-II on soil temperature t_p (cold season)

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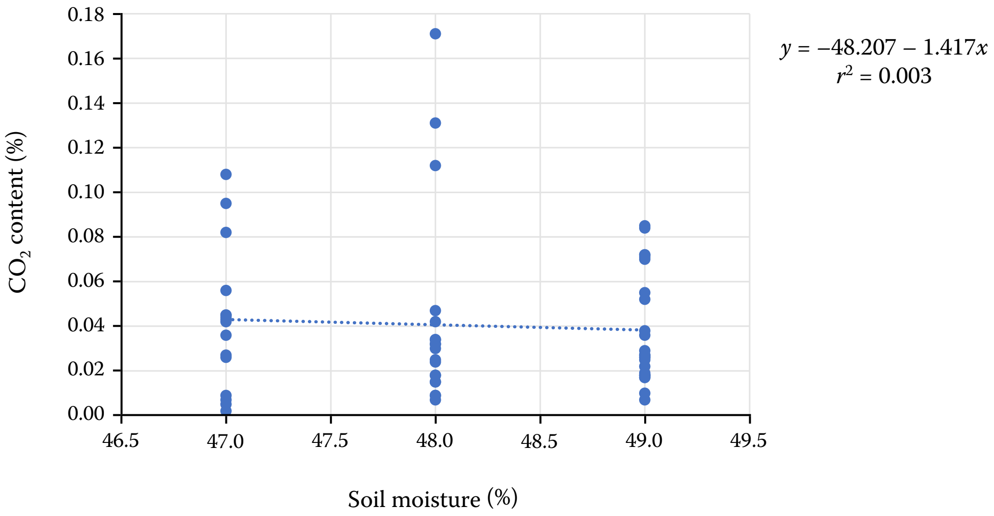

Figure 8. Dependence of CO_2 concentration in CO_2-II on relative soil moisture ρ (cold season)

ured characteristics were recorded in time. Figure 9 shows an essential fact that even in the warm period of the year, the CO_2 concentrations in the data files CO_2-I and CO_2-II significantly differed from each other and that the values of CO_2 concentrations in CO_2-I (compacted soil) were significantly higher than the values of CO_2 concentrations in CO_2-II (non-compacted soil).

Within the parameter 'Assessment of the similarity of CO_2 content in soil air' in the compacted and non-compacted soil, the similarity of the CO_2 concentrations was compared between CO_2-I and CO_2-II. The diagram in Figure 9 and the statistical assessment (Table 2) demonstrate a significant difference between the two data files. Concentrations of CO_2 in CO_2-I (compacted soil) are notably higher than those in CO_2-II (non-compacted soil). Based on this fact, it is possible to state that the influence of soil compaction on the increased content of CO_2 in soil air was unambiguously demonstrated.

Another research task was to assess the degree of correlation between the concentration of CO_2

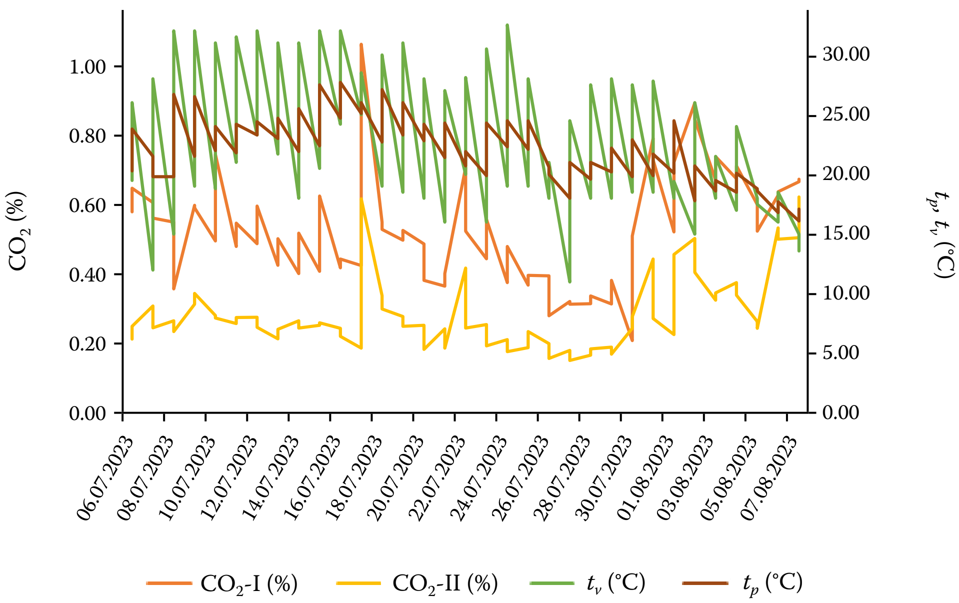

Figure 9. Diagram of the CO_2 concentrations in soil air, air temperatures t_v and soil temperatures t_p in the warm period from July 6 to August 7, 2023

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Table 2. Statistical assessment of the dependence of CO_2 content in soil air on some factors in the period from July 6 to August 7, 2023

Parameter	Calculated value of decisive quantity	Critical values of decisive quantity	Relation between the calculated and critical value of decisive quantity	Final evaluation
Assessment of similarity of CO_2 content in soil air of compacted and non-compacted soil – data files CO_2-I and CO_2-II	6.077	$t_{0,.25} = 1.960$ $t_{0.005} = 2.576$	t (6.077) > $t_{0.025}$ (1.960) t (6.077) > $t_{0.005}$ (2.576)	statistically significant difference between CO_2-I and CO_2-II data; the effect of soil compaction on increased CO_2 content was clearly demonstrated
Assessment of the degree of dependence of CO_2 content in CO_2-I on air temperature t_v	0.146	$r_5 = 0.2546$ $r_1 = 0.3306$	r (0.146) < r_5 (0.2546) r (0.146) < r_1 (0.3306)	no statistical dependence, CO_2 content does not depend on air temperature t_v
Assessment of the degree of dependence of CO_2 content in CO_2-I on soil temperature t_p	0.163	$r_5 = 0.2546$ $r_1 = 0.3306$	r (0.163) < r_5 (0.2546) r (0.163) < r_1 (0.3306)	no statistical dependence, CO_2 content does not depend on soil temperature t_p
Assessment of the degree of dependence of CO_2 content in CO_2-I on relative soil moisture ρ	0.195	$r_5 = 0.2546$ $r_1 = 0.3306$	r (0.195) < r_5 (0.2546) r (0.195) < r_1 (0.3306)	no statistical dependence, CO_2 content does not depend on relative soil moisture ρ
Assessment of the degree of dependence of CO_2 content in CO_2-II on air temperature t_v	–0.271	$r_5 = 0.2546$ $r_1 = 0.3306$	r (–0.271) < r_5 (0.2546) r (–0.271) < r_1 (0.3306)	no statistical dependence, CO_2 content does depend on air temperature t_v
Assessment of the degree of dependence of CO_2 content in CO_2-II on soil temperature t_p	–0.314	$r_5 = 0.2546$ $r_1 = 0.3306$	r (–0.314) < r_5 (0.2546) r (–0.314) < r_1 (0.3306)	no statistical dependence, CO_2 content does not depend on soil temperature t_p
Assessment of the degree of dependence of CO_2 content in CO_2-II on relative soil moisture ρ	0.705	$r_5 = 0.2546$ $r_1 = 0.3306$	r (0.705) >r_5 (0.2546) r (0.705) > r_1 (0.3306)	statistical dependence exists, CO_2 content depends on relative soil moisture ρ

CO_2-I – data file with the CO_2 content in soil air of compacted soil; CO_2-II – data file with the CO_2 content in soil air of non-compacted soil; ; t – temperature; r – correlation coefficient

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in CO_2-I and air temperature t_v. Results of the statistical assessment showed (Table 2) that the value of the correlation coefficient differed only a little from zero and that the dependence of variable *y* on variable *x* was very low; thus, the correlation relationship does not exist. Therefore, it can be stated that in the data file CO_2-I, the content of CO_2 does not depend on air temperature t_v (Figure 10).

A further subject of research was to assess the degree of correlation between the CO_2 concentration in CO_2-I and soil temperature t_p. Results of the statistical assessment showed (Table 2) that the value of the correlation coefficient differed only slightly from zero and that the dependence of variable *y* on variable *x* was low; thus, a correlation relationship existed. Therefore, it can be stated that in CO_2-I, the CO_2 content does not depend on soil temperature t_p (Figure 11).

The next research task was to assess the degree of correlation between the concentration of CO_2 in CO_2-I and relative soil moisture ρ. Results of the statistical assessment showed (Table 2) that the value of the correlation coefficient differed only a little from zero and that the dependence of variable *y* on variable *x* was low; thus, the correlation relationship does not exist. Therefore, it is possible to state that the CO_2 content in CO_2-I does not depend on relative soil moisture ρ (Figure 12).

The next research task was to assess the degree of correlation between the concentration of CO_2 in the data file CO_2-II and air temperature t_v. Results of the statistical assessment showed (Table 2)

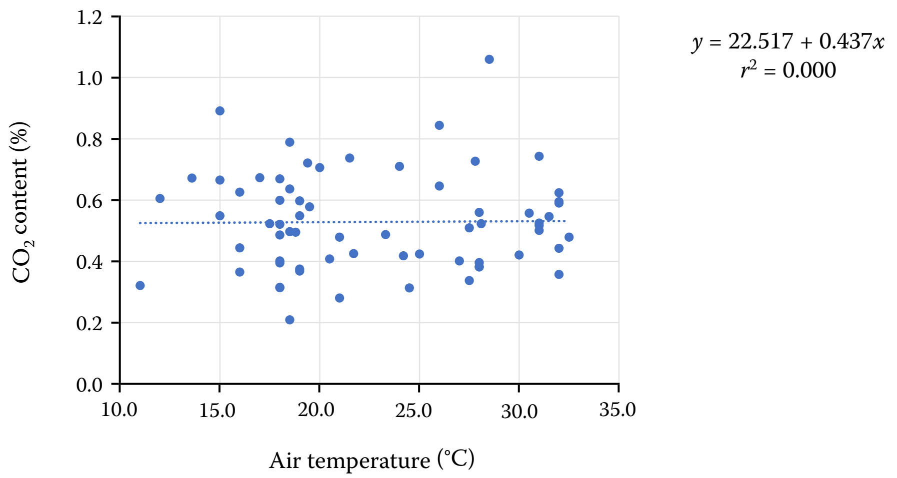

Figure 10. Dependence of CO_2 concentration in CO_2-I on air temperature t_v (warm season)

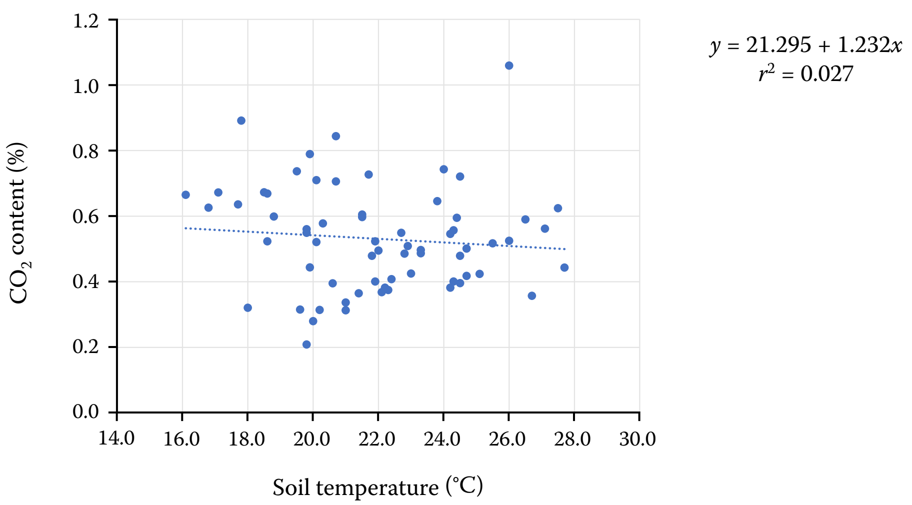

Figure 11. Dependence of CO_2 concentration in CO_2-I on soil temperature t_p (warm season)

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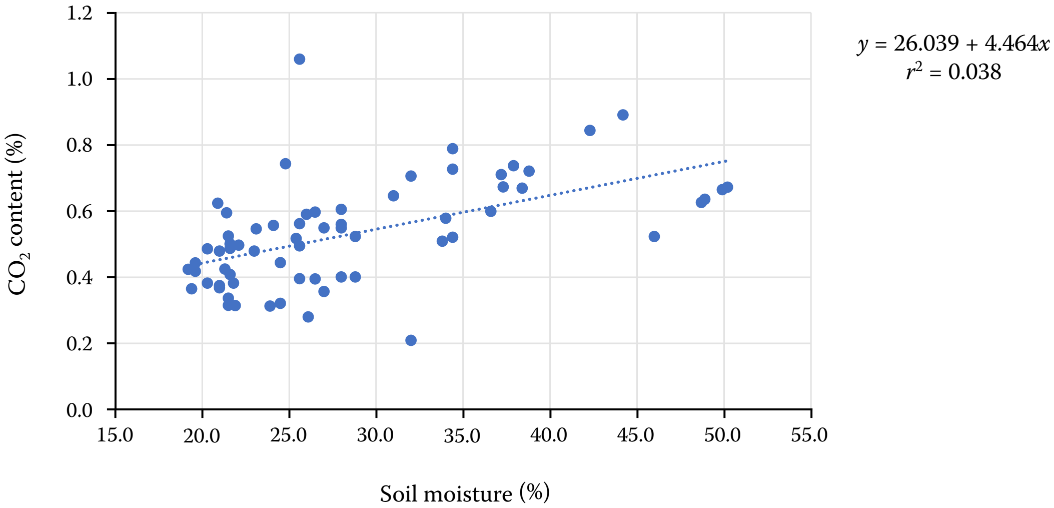

Figure 12. Dependence of CO_2 concentration in CO_2-I on soil moisture ρ (warm season)

that the value of the correlation coefficient differed only a little from zero and that the dependence of variable y on variable x was very low; thus, the correlation relationship does not exist. Therefore, it can be stated that in CO_2-II, the content of CO_2 did not depend on air temperature t_v (Figure 13).

The next research task was to assess the degree of correlation between the concentration of CO_2 in the data file CO_2-II and soil temperature t_p. Results of the statistical assessment showed (Table 2) that the value of the correlation coefficient differed slightly from zero and that the dependence of variable y on variable x was low; thus, a correlation relationship existed. Therefore, it can be stated that in CO_2-II, the content of CO_2 does not depend on soil temperature t_p (Figure 14).

The next research task was to assess the degree of correlation between the CO_2 concentration in CO_2-II and relative soil moisture ρ. Results of the statistical assessment showed (Table 2) that the value of the correlation coefficient slightly differed from zero and that the dependence of variable y on variable x was strong; thus, a correlation relationship exists. Therefore, it is possible to state that in CO_2-II, the content of CO_2 depends on relative moisture content ρ (Figure 15).

Summarising the research results, we can state that the direct dependence between the factor

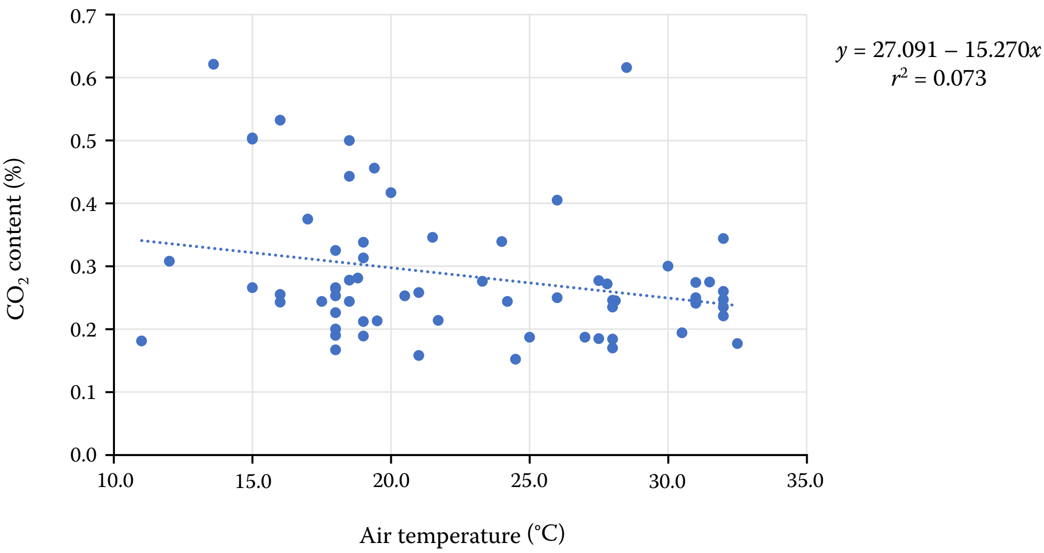

Figure 13. Dependence of CO_2 concentration in CO_2-II on air temperature t_v (warm season)

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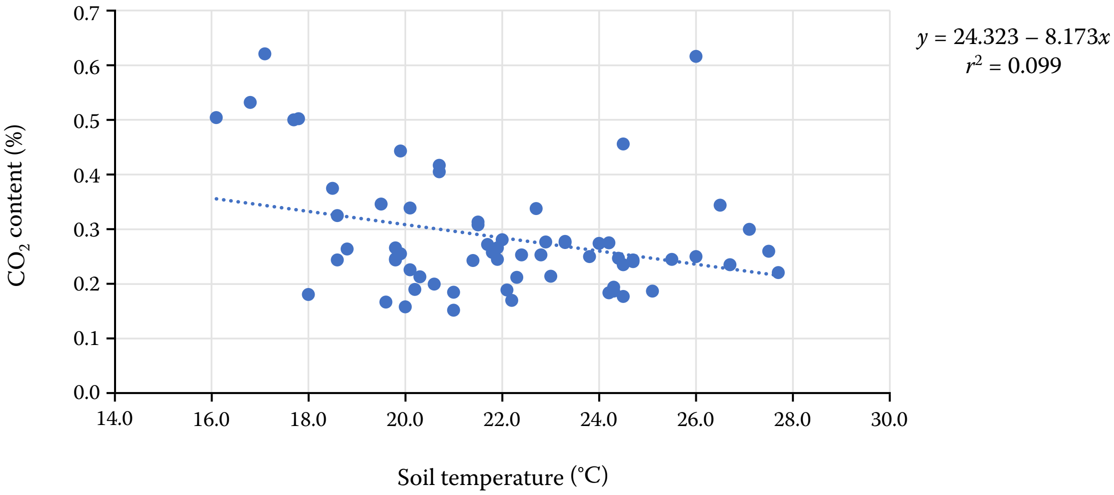

Figure 14. Dependence of CO_2 concentration in CO_2-II on soil temperature t_p (warm season)

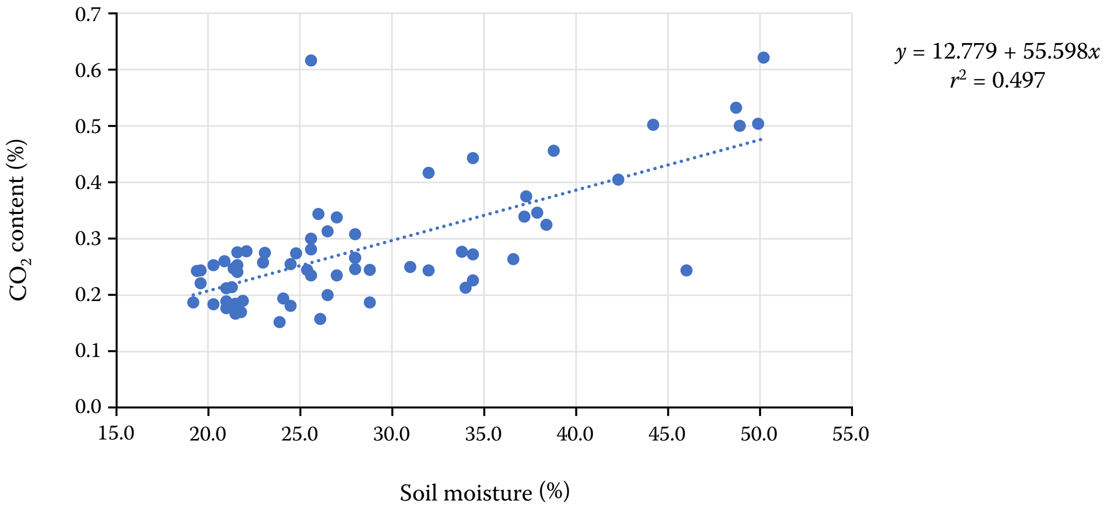

Figure 15. Dependence of CO_2 concentration in CO_2-II on soil moisture ρ (warm season)

of soil compaction and increased CO_2 concentration in soil air was confirmed. Significant differences between the concentrations of CO_2 in the soil air of compacted and non-compacted soil were clearly shown in spite of the fact that the soil compaction was relatively moderate (caused by a single passage of heavy machine wheels along the track in which the CO_2 concentration was measured as in the compacted soil). The impact of soil compaction by the traffic of heavy machines on the degree of CO_2 concentration in soil air is of long-term character; significant differences in the concentration of CO_2 between the compacted and non-compacted soil persisted from the cold to the warm season of the year. The increase in CO_2 concentration showed identically in the data measured in both seasons of the year (cold and warm ones): the concentration of CO_2 in soil air in the compacted soil was always significantly higher than the concentration of CO_2 in the non-compacted (natural) soil on the control plot.

For more precise conclusions in this sense, a statistical analysis of the dependence of the CO_2 concentration on the air temperature was carried out for both periods (cold and warm ones). The values of the statistical parameters of the relationship between CO_2 concentration and air temperature t_v show that the correlation coefficient r (0.218) is higher than the threshold value for the significance level of 0.05 (0.1946) and is slightly lower than the threshold value for the significance level of 0.01 (0.2540). An important

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finding emerges from this observation: the concentration of CO_2 in soil air is dependent on the ambient air temperature.

The influence of other factors (soil temperature, air temperature and soil moisture) was demonstrated only in two cases (see Table 1 and Table 2). Thus, the fundamental factor appears to be the soil compaction by wheel traffic of heavy machines.

DISCUSSION

From the above results there is a clear observation of a fundamental difference in the CO_2 concentration in the soil air within the soil compacted by one pass of a heavy machine in comparison with the non-compacted soil. Thus, the main hypothesis (H_1) of the study on the effect of soil compaction on the increase of CO_2 content in soil air was confirmed.

Mechanised logging operations commonly used in forestry can unfavourably affect the soil environment. Several research studies have shown that the excessive operation of forest machines such as harvesters or forwarders results in soil disturbance, including soil compaction (Poltorak et al. 2018; Picchio et al. 2020). Koreň et al. (2015) agree with the statement and add that felling of trees, timber skidding and timber transport by heavy machines across the forest soil result in visible soil compaction and rutting. This can cause soil degradation in forest ecosystems as the traffic of machines influences important structural characteristics of the soil (Ampoorter et al. 2007). The affected area and severity of the impact depend on the soil type and condition, climate (precipitation and temperature among other things), logging system and machine characteristics (Picchio et al. 2012; Cambi et al. 2015). This is the opinion of the authors of this research as well.

One of the first visible indicators of damage to soil by the wheel traffic is excessive deformation of traffic areas (ruts) (Najafi et al. 2009), which results in soil compaction. Disadvantages of soil compaction, such as decreased rate of water infiltration and decreased air permeability in the soil, affect the chemical characteristics of the soil.

Our research revealed that the soil compaction results in increased soil content of CO_2 both in the winter and summer periods. This is consistent with Conlin and van den Driessche (2000), who recorded increased CO_2 with the compaction of soil based on measurements taken for 3 years. Some authors (Gaertig et al. 2002; Goutal et al. 2012) also recorded a greater amount of CO_2 in compacted soils. Measurement in all forest stands also demonstrated a significant increase in CO_2 content after compaction (Allmanová et al. 2014). Allmanová et al. (2014) added that the compacted soils contained six times more CO_2 than the non-compacted ones. Kuzyakov (2006) reported a significant correlation between soil compaction and CO_2. In his research, the soil compacted to 1.5 $g \cdot cm^{-3}$ retained 32% more CO_2 as compared with the non-compacted soil (Kuzyakov 2006). Other authors agreed with our statement that CO_2 concentrations in the compacted soil were higher than those in the non-compacted soil (for example Ponder 2005; Goutal et al. 2013; Epron et al. 2016).

Contrariwise, there are authors (Beare et al. 2009; Busman et al. 2021) reporting other results. Specifically, Beare et al. (2009) claimed that the content of CO_2 in non-compacted soils in their research was more than double as compared with compacted soils. Results of research published by Busman et al. (2021) indicated that the total efflux of CO_2 from the soil during the period of 12 weeks was higher in the compacted soil compared with the non-compacted soil.

Soil moisture characteristics are inseparable from the regulation of CO_2 in the soil (Gui et al. 2023). Results of our research demonstrated that in the winter period, the CO_2 content does not depend on relative soil moisture either in compacted or in non-compacted soil. It was, however, shown that in the summer period, the content of CO_2 in the non-compacted soil depends on relative soil moisture. Our research results partly differ from results published in literature (Kuzyakov 2006; Novara et al. 2012; Li et al. 2022). Results of Kuzyakov (2006) show a significant correlation between the rainfall duration and the increased soil moisture content and CO_2 concentration. A similar opinion was expressed by Novara et al. (2012), who reported that the soil emissions of CO_2 were also significantly affected by rain and that CO_2 emissions in the soil which was exposed to rain were up to 26% higher than in the soil which was not exposed to rain. Li et al. (2022) pointed out that the gradual drying out of soil opens diffusion paths, which mitigates oxygen restriction and allows higher production of CO_2 in the soil. The au-

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thors of many studies (Fierer, Schimel 2003; Miller et al. 2005; Ruser et al. 2006) mentioned that the production of CO_2 significantly increases when the soils are moist. Beare et al. (2009) informed that the production of CO_2 was approximately 2.5 times higher immediately after soil wetting in the non-compacted soil than in the compacted soil. Goutal et al. (2013) stated that the highest soil values of CO_2 were recorded in the period with a great fluctuation of soil water content. Pla et al. (2017) found that the higher production of CO_2 concentration was observed after rain, i.e. in the moist soil. Several research studies were focused on the effect of soil moisture on its compaction (Trautner, Arvidsson 2003; Shahgholi, Abuali 2015). Their results (Trautner, Arvidsson 2003) showed that soil compaction occurs much less in the dry soil but that it significantly increases with increasing soil moisture and load. Shahgholi and Abuali (2015) were of a similar opinion, claiming that the soil compaction considerably increases with the increasing soil moisture.

Some authors (Chen et al. 1993; Phillips, Nickerson 2015; Kaushal et al. 2023) investigated the effect of temperature and relative moisture on CO_2 efflux from the soil. Kaushal et al. (2023) recorded a maximum CO_2 efflux from the soil during the rainy season, reasoning with increased soil moisture and soil temperature. Chen et al. (1993) and Phillips and Nickerson (2015) concluded that soil moisture and soil relative temperature are important factors affecting the rate of CO_2 efflux from the soil.

In other research, Goutal et al. (2012) revealed that low soil temperatures are connected with lower CO_2 production. In most measurements, this statement agrees with our research during the winter season when lower values of CO_2 in the soil were recorded at lower temperatures than at higher temperatures both in compacted and non-compacted soils. The summer period observed in our research showed opposite results. Badraghi et al. (2021) was convinced that the production of CO_2 in the soil is regulated by soil temperature and that pedoclimatic variables depend on the soil depth (Goutal et al. 2012). Goutal et al. (2012) suggested that the relationship between CO_2 and pedoclimatic variables, including soil temperature, is weak.

Results of our research in the winter period revealed that the content of CO_2 in the compacted soil depends on soil temperature. Nevertheless, another finding was that neither the content of CO_2 in the soil compacted in the winter period, nor that in the soil compacted or non-compacted in the summer period, depends on soil temperature. Bekele et al. (2007) informed that regression coefficients related to soil temperature and soil moisture content differ in dependence on the soil treatment and its depth. Goutal et al. (2012) claimed that soil temperature and soil air-filled porosity affect most changes in CO_2. In the research of Ponder (2005), the rate of CO_2 efflux from the soil was positively correlated with the soil temperature.

Our research, including research studies of many other authors, indicates that the soil compaction by the traffic of heavy machines significantly increases the concentration of CO_2 in soil air. A measure frequently used in forest practice to improve the bearing capacity of forest soil and to mitigate its compaction is the use of logging residues (branches) placed on the machine path. The logging residues spread the machine weight over a larger area, thus reducing the pressure of wheels onto the soil surface of the machine path (Ampoorter et al. 2007; Jourgholami et al. 2020). However, Hutchings et al. (2006) stated that logging residues cannot fully prevent soil surface compaction. Other possibilities are to reduce air pressure in tyres (Mohsenimanesh, Ward 2010), to modify tyre dimensions (Haas et al. 2016; Marušiak et al. 2024), or to use machines with a tracked or half-tracked undercarriage (Haas et al. 2016).

CONCLUSION

Evaluating the research results, we can state that the main hypothesis (H_1) that assumed the CO_2 concentrations to significantly differ in the compacted soil from the CO_2 concentrations in the non-compacted natural soil was confirmed, as well as the fact that the differences would be exhibited both in the cold and in the warm period of the year. Other expected consequences (CO_2 concentration will depend on some external factors such as air temperature t_v, soil temperature t_p or relative soil moisture ρ) were confirmed only partly. A fact to be derived from our research findings is that the forest soil compaction caused by the traffic of heavy machines, and in the given case demonstrated by the increased concentration of CO_2 in soil air, is of long-term character, and relative differences in CO_2 concentrations between the compacted and non-compacted soil do not show a larger change.

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