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SOIL CARBON DIOXIDE CONCENTRATION AND EFFLUX CHANGES IN RUTS AFTER HEAVY MACHINE PASSES

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Abstract: *Heavy loaded forwarders and similar forest machinery moving along the same rut gradually push back soil at the rut edges, while soil is compressed and its porosity decreases at the rut centre. Rut surface shows markedly higher deterioration of soil gasses efflux in compare with undisturbed area. It was founded by continual measurement with Vaisala device with infra-red probes, that the soil CO_2 concentration in rut was 12 times higher than in undisturbed soil (4,2 % versus 0,5 %). The CO_2 efflux from ruts surface was 50 % lower compared to undisturbed area (0,15 % versus 0,35 %). Poorer CO_2 efflux in soil caused by machine pass can negatively influenced tree root systems and it is possible that it is one measurable indicator of machine pass negative influence on forest environment.*

Introduction

CO_2 release from the soil surface or soil respiration is considered to be the main part of the biospheric cycle of carbon because it creates about ¾ of the total ecosystem respiration (Law et al. 2001). In recent years, CO_2 release from soil has been the subject of intensive research. A method of the infrared analyser of air is regarded a suitable principle for the continual measurement of CO_2 content in soil air.

Only after 2000, new infrared sensors of the CO_2 content in air were developed. They are very small and can be inserted into soil in the form of a probe. In connection with an electronic measuring device they make possible the continual measurement in outdoor conditions. Hirano et al. (2000) used as the first these small GMD 20 sensors of the Finnish company Vaisala for measuring the soil respiration in broadleaved forests of Japan and thus demonstrated the suitability of this method. Another authors, e.g. Tang et al. (2003), tested the use of these devices (GMT 221 or GMT 222) for the measurement of soil respiration under conditions of savannahs in California. The Institute of Forest and Forest Products Technology, MUAF Brno developed its actual methodology and obtained several-year experience in evaluating impacts of logging/hauling technologies on forest soil by the measurement of CO_2 concentration in soil air. Main findings obtained are the subject of this paper, which contains information about results of soil surface CO_2 efflux measurements influenced by machine pass.

Methods

Within the study, attention was paid to the assessment of the knowledge of CO_2 release from soil to evaluate potential impacts of the travel of heavy machines on soil and roots of trees. The passage of heavy machines causes significant changes in the soil structure, i.e. compaction, which was dealt with by a number of authors.

By means of the measurement of the CO_2 content concentration in soil air it is possible to asses the immediate condition of soil aeration. Impaired soil aeration can result in stopping the growth of fine roots. Particularly in soils with the higher content of clay the origin of impermeable layers can occur, which can even result in the necrosis of roots (at increased soil moisture). Thus, the site stability can be endangered. Moreover, drought stress can occur, which is caused by the small volume of pores or decreased water capacity of soil (Güldner 2002). Methods on the basis of gas chromatography used so far (Güldner 2002) were not available for our research team and with respect to the requirement of the continual registration of the time course of the CO_2 concentration in soil air in the forest environment were not even particularly satisfactory. Thus, a method was developed based on devices of a Finnish company Vaisala, i.e. measuring instruments of the CO_2 concentration, viz. CARBOCAP GMT 221 or Carbon Dioxid Meter GM70 and measuring probes CARBOCAP GMP 221 with a basic measuring range to 3% (5%) of CO_2 and accurate to 0.02%. The probe uses the principle of measuring the absorption of CO_2 infrared beam included in air. The probe is of a cylinder form; its length is 95 mm and diameter 18.5 mm. To the upper side of the probe body an interconnection cable is attached connecting the probe with an apparatus for the measurement of the CO_2 concentration.

Inside of the lower part of the probe body, there is the actual infrared CO_2 sensor covered by a grid and a membrane. Openings in the grid make possible air to penetrate to the sensor protecting at the same time the sensor from pollution.

These devices were arranged into a measuring chain, which included a temperature gauge, Minikin 1 data logger enabling to record data (CO_2 concentration and temperature) at 10 minutes and 24 V power supply. For the measuring probe, a plastic tube case was constructed of a diameter of 30 mm and length 12 cm, the upper side of which was provided with a ring 7 mm wide. In the lower half of the case wall, a system of holes was drilled making possible the passage of soil air to the case space at the sides. At the same time, air penetrates into the space by the lower opening of the case. This case is sealed by a rubber plug going through the probe body in the upper part of the case. The case is inserted into a calibrated opening in soil reaching a depth of about 12 cm.

In the course of compaction, decreasing the soil porosity and its air capacity occurs. The soil aeration gets worse and it is possible to suppose that CO_2 accumulation can occur under the compacted layer of soil, which (particularly in some cases on soils with higher contain of clay) can create poorly permeable or even entirely impermeable zone preventing the CO_2 release from soil to atmosphere. Methodology of research was appended in 2009 to confirm or overcome hypothesis that CO_2 efflux is worse due to impermeable zone on soil surface. It is possible to expect by hypothesis that higher CO_2 concentration in soil air causes decrease CO_2 efflux from compacted soil surface and conversely.

Figure 1 Probe with cover for measuring of CO_2 efflux (red), probe for CO_2 concentration in soil air on right

Figure 2 Measuring instruments CARBOCAP GSM70 with measuring probes of CO_2 efflux from soil and CO_2 concentration in soil air on control plot

Method filling up is based on adaptation of measuring probes and creating of CO_2 measuring procedure in restricted space above of soil surface. Measuring probe of CO_2 volume in air was equipped with plastic cover of conical shape with 120 mm basis. Measuring probe is closely allied in upper hole and its sensor is 15 mm high under bottom border of plastic cover (Figure 1, 2).

Plastic cover with measuring probe is placed to soil surface, cover contact edge with soil is caulked and then measurement of CO_2 concentration in air inside of plastic cover. Values of CO_2 concentration are registered automatically (generally 60 minutes) by measuring instrument which is connected with devices (GMT 221 or GMT 222).

Method modification allows both measurement of CO_2 concentration in soil air in surface soil layer and soil surface CO_2 efflux in parallel both on places compacted by machine passage and on control places.

Results

A. Measurement of CO_2 concentration in soil air

Measurements were carried out in a number of localities using always two probes one of them being placed in soil compacted by the passage of a forwarder, the second one served as a check probe being placed in natural undisturbed soil.

The actual measurement of CO_2 concentration is carried out in two forms:

- **Short-term measurements** followed the development of the CO_2 concentration increase immediately after soil compaction, the time of measurement took about 2 hours after placing the probes into soil.
- **Long-term measurements** were carried out on an established experimental plot on sandy-loam soil, the surface of which was partly mechanically compacted to a similar level, which was caused by the passage of heavy machines. Within the experiment, long-term continual monitoring the level of CO_2 concentration in soil air was carried out from 1 January 2007 to 27 December 2008.
- The measurements were completed by the evaluation of other soil characteristics, such as penetration resistance, soil moisture, soil porosity etc.

Some **results of short-term measurements** are included in **Figure 3**. In the given case, measurements were carried out at several localities of Forest District Telc. Soil compaction was achieved by 10 passages of a forwarder, the total weight of which was 18 t.

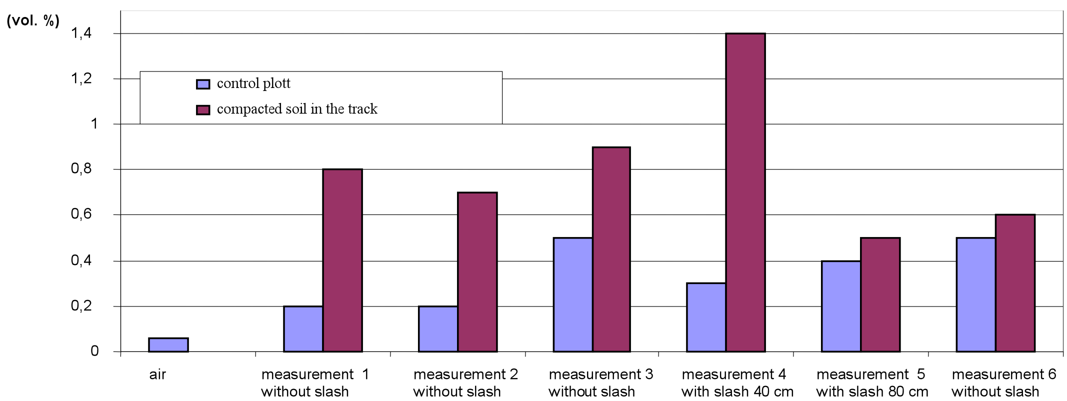

Figure 3 Results of measurements of the CO_2 concentration in air in soil compacted by the passage of machines

Soil compaction in the tractor track in a layer up to 15 cm expressed by penetration resistance amounted to 0.22 MPa (as against 0.17 MPa at check). These measurements characterize the CO_2 concentration in soil air always after about 2 hours from the insertion of probes into soil. The measurements were carried out at two places of Locality 8: measurements No. 1 on an area with soil moisture 38% hm. Measurements Nos. 2 – 6 were carried out on an area where it was possible to find out places with various soil moisture and to direct suitably the tractor to create measuring places. Thus, particular measurements were situated to places with various soil conditions: measurements No. 2 brownish-yellow loamy soil with the admixture of sand and fine soil skeleton, moisture 23% hm., measurements Nos. 3 and 4 darkly brownish-yellow sandy loam soil, heavily penetrated by roots, 38% hm., measurements Nos. 5 and 6 darkly brownish-yellow sandy loam soil, heavily penetrated by roots, soil moisture 21% hm. At the same time, effects of the slash cover were tested on physical changes in soil and thus also on soil respiration.

Examples of the course of long-term measurements are demonstrated in diagrams in **Figure. 4a, b** and **5a, b**. These diagrams and diagrams in **Figure 3** show that in the course of long-term and short-term measurements, measured and recorded values of the concentration of CO_2 are always markedly higher in compacted soil (often even severalfold) than at control plots. Maximum values of the CO_2 concentration in compacted soil in tracks reached nearly values exceeding 3%, at control plots only about 0.6%.

- In compacted soils as well as at a control plot, there is an evident effect of the soil temperature on the content of CO_2 – with decreasing temperatures the content of CO_2 decreases. It is evident both from the long-term aspect (eg in the winter season), but also in the course of shorter periods.
- Increasing the soil moisture causes an increase in the concentration of CO_2 which becomes evident particularly during precipitation – rain.
- There is a clear relationship between the soil moisture level and immediate temperature when the synchronous increase in soil moisture and temperature results in higher increase of CO_2 concentration than the single increase of one or the second quantity. However, this is only a preliminary finding because there is not a sufficient number of data available to create a mathematical model.
- Aeration possibilities of compacted soils are thus markedly worsened as against undisturbed soils.
- A method of the determination and registration of CO_2 concentration and at the same time of soil and air temperature by continuous measurements using the device chain described above can be considered to be suitable for the given purpose.

Monitoring the effect of various modifications of wheel chassis on factors determining soil compaction was interesting (bare tires, tires equipped with wheel-tracks with narrow cross members or wheel-tracks with wide cross members). In trial plots in Forest District Telc, dependence of soil compaction was determined on the frequency of passages of a 24 500 kg John Deere 1110D forwarder along laid out tracks. The measurement was carried out after 1, 5 and 10 passages.

In evaluating standard pedological indicators (porosity, air capacity), it is possible to state that in pseudogley soil units, which are affected by smaller intensity of soil water, changes in physical properties after the passage of logging and hauling machines are very marked. In the tractor wheel track, soils are often degraded to the level of the gley soil environment. Forwarders equipped with wheel-tracks with narrow cross members (eg Eco-Track type) show the most negative effects, viz. in upper soil layers up to about 15 cm. On the other hand, effects of passages of tractors equipped with low-pressure floatation tires become evident in subsurface horizons at a depth of about 20 – 25 cm.

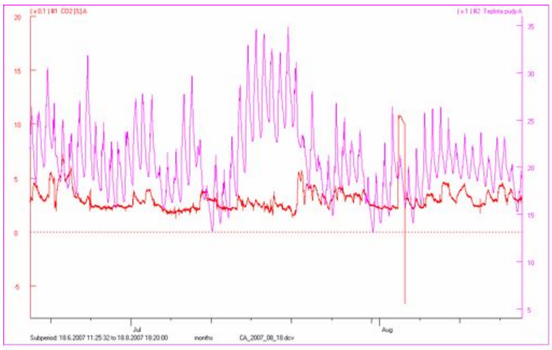

Figure 4a A detail of the CO_2 measurement record – 18 June to 18 August 2007 – control plot

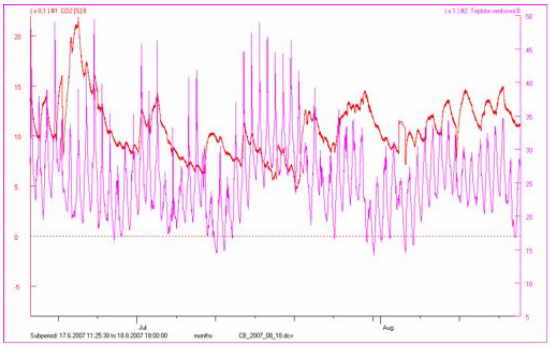

Figure 4b A detail of the CO_2 measurement record – 18 June to 18 August 2007 – compacted soil in a track

Values of soil parameters approach a risk level (reduced volume weight ≥ 1.5 g.cm^{-3}, porosity < 35%, maximum capillary capacity < 30% and minimum air capacity < 3%). A positive (favourable) effect has been, however, found viz. that at the application of wheel-tracks with wide cross members (eg Eco-Baltic type) on floatation tires with a wide track, pedological characteristics change only gradually even after multiple passages as compared with control plots. Differences, particularly in surface layers, are negligible in basic characteristics being only relative.

The use of wheel-tracks with wide cross members on chassis of forwarders at logging technologies on sites of category P (pseudogley) and G (gley) is, therefore, clearly substantiated. Except the disturbance of the integrity of holorganic and organomineral horizons physical properties remain on the level of optimum or initial values. Also results of penetrometry prove consistently at both sites that the the highest penetration resistance 0.6 MPa was found in using wheel-tracks Eco-Track, these wheel-tracks disturb the integrity of the upper soil horizon due to their profile and at passages with the higher frequency deeper transport ruts occur. In case of ride on wheels without wheel-tracks, penetration resistance 0.4 – 0.5 MPa was measured and at the use of wheel-tracks with wide cross members Eco-Baltic the smallest penetration resistance of 0.3 – 0.4 MPa was found. The penetration resistance of soil on the control plot amounted to 0.25 – 0.35 MPa.

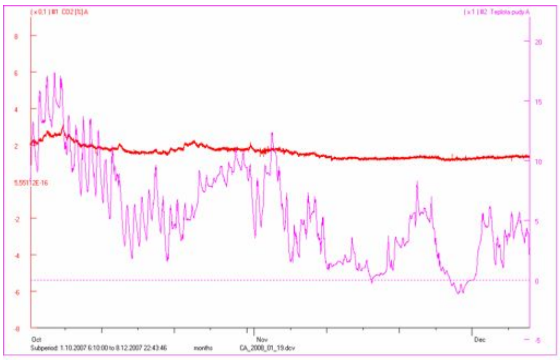

Figure 5a A detail of the CO_2 measurement record – 1 October to 8 December 2007 – control plot

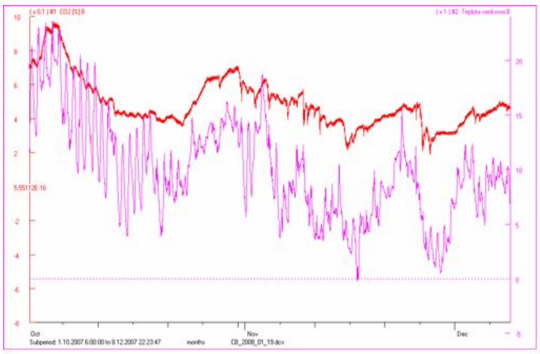

Figure 5b A detail of the CO_2 measurement record – 18 June to 18 August 2007 – compacted soil in a track

At the determination of changes in CO_2 concentration in soil it is evident that it is possible to observe results surprisingly analogical to changes of standard pedological characteristics and penetrometry mentioned above. Short-term measurements of CO_2 concentration showed that the highest increase in CO_2 concentration to a value of 3.0 – 3.2% during 60 minutes was found in a drive created by the passage of a tractor with wheel-tracks with narrow cross members Eco-Track. Lower concentrations of CO_2 up to a value of 1.4% were measured in a roadway when using only low-pressure tires.

The lowest level of CO_2 concentration within the limits 0.8 –1.2% was measured at the use of wheel-tracks with wide cross members Eco-Baltic. The level of CO_2 concentration on a control plot amounted to 0.4 – 0.6%. Thus, it is possible to note that particularly on soils of low bearing capacity with the higher level of groundwater the use of wheel-tracks Eco-Baltic is most suitable, namely both on pseudogley and gley sites.

Although the number of measurements of the content of CO_2 in soil compacted by the passage of heavy machines is not too extensive it is possible to note surprisingly significant results, which point unambiguously to markedly impaired aeration properties of soil in tracks compacted by wheels of forwarders as against control plots (Neruda, Ulrich 2004, 2006). Thus, CO_2 accumulates mostly in compacted soils, which are characterized by the higher content of clay particles.

B. Combined measuring of CO_2 concentration in soil air and CO_2 efflux from soil surface

Research was done from July 20th to 24th 2009 on six research plots at Military Forests and Farms, state public enterprise, Horní Planá Division (48°46´2´´N, 14°1´57´´E, altitude ca 900 m).
Four research plots were situated in spruce forest stand 2a8 with average terrain slope of 15°. Tending felling was done by harvester John Deere 770 D, average width of strip road 4 m and 24 m spacing between strip roads. Measurements were done on strip roads ruts after machine passage and on control plots (unaffected by machine passage).

Research plots 5 and 6 were situated on strip roads in spruce stand 2b2 where timber from final felling was skidded by skidder. Average terrain slope was 8°. Measurements were done on strip roads ruts after machine passage and on control plots (unaffected by machine passage).

Soil conditions on all plots were similar, i.e. loamy sand to sand clay soil. Soil is with subsoil weathering process – brunification, intermediate deep soil with soil skeleton in bottom part. Loose soil is in upper layers change consistency with depth to slightly medium soil density. Friable structure is mostly medium size friability (3-4 mm). Ingredients of coarse sand are growing with depth and optimize water and air conditions. Consistently stabile. Litter fractions with fermentative layer and high root density soil horizont of natural humification make optimal condition for *Picea abies*.
Measurement results are shown in Tab. 1, examples of CO_2 concentration in soil air changes and CO_2 efflux records are displayed in Figure 6a and Figure 6b.

Table 1. Measurement results of CO_2 concentration in soil air and CO_2 efflux on research plots 1 - 6 (CO_2 concentration after 60 minutes)

Plot	Machine/ number of passages	Measurement place	Soil moisture (%)	Rut depth (cm)	Rut mound high (cm)	Slash layer on strip road (cm)	CO_2 soil (%)	CO_2 efflux (%)	Soil penetration resistance in 20 cm depth (MPa)
1	Harvester + forwarder/+6	rut	35	14 - 16	3 – 6	20	4,52	0,14	1,8 ; 4,0**)
		control	29	-	-	-	0,43	0,28	2,0
2	Harvester + forwarder/4	rut	39; 44*)	7 - 9	2 - 4	25	4,90	0,11	2,2
		control	21	-	-	-	0,32	0,25	2,3
3	Harvester + forwarder/+6	rut	40*)	12 - 14	-	0	3,21	0,12	3,2**)
		control	21	-	-	-	0,33	0,22	2,5
4	Harvester JD 770/2	rut	27	8 - 12	5 - 7	25	1,12	0,15	4,2
		control	22	-	-	-	0,33	0,41	3,6
5	Empty skidder /+6	rut	40	12 - 18	13 - 30	0	4,30	0,14	5,0
		control	32	-	-	-	0,44	0,27	2,0
6	Skidder with load /+6	rut	42	25 - 30	15 - 20	0	3,92	0,12	6,0
		control	35	-	-	-	0,41	0,35	3,0

Legend: *) soil moisture in rut without slash layer; **) penetration resistance on strip road without slash layer

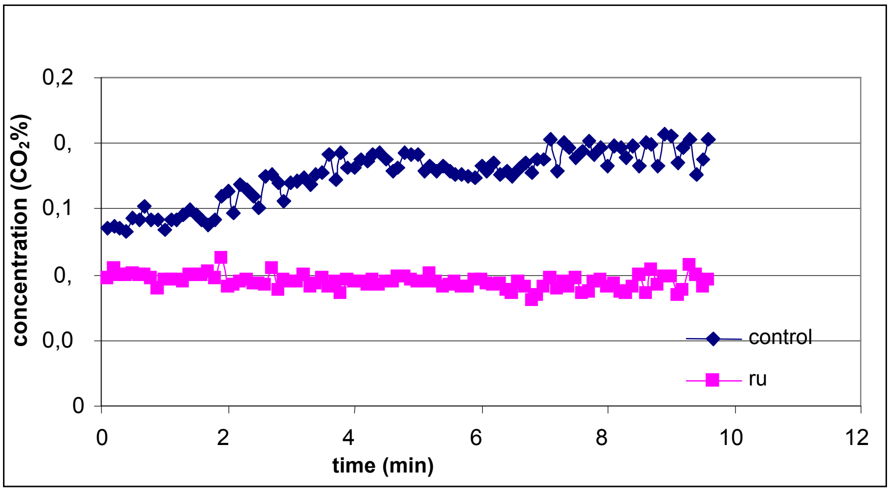

Figure 6a Example of CO_2 efflux measurement from soil surface on plot 3

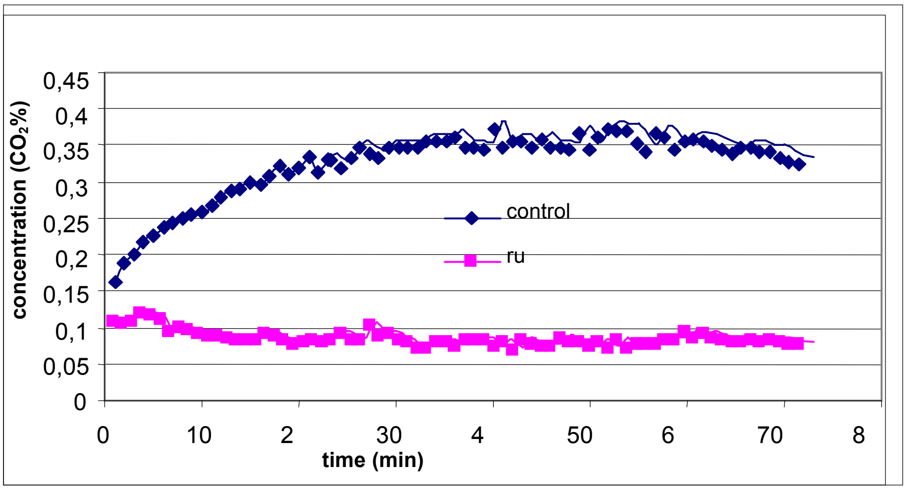

Figure 6b Example of CO_2 efflux measurement from soil surface on plot 6

Data show interesting results. Indirect dependence between CO_2 concentration in soil air and CO_2 concentration closed to soil surface is perspicuous on all plots (see Tab. 1 and Fig 6a, b). Scilicet, CO_2 efflux is always higher on control plot than on rut and contemporaneously CO_2 concentration in soil air on control plot is markedly lower than CO_2 concentration in soil air in rut.

Conclusion

If the concentration of 0.6% CO_2 in soil air is considered to be a boundary value indicating significant changes in the soil structure with consequences for the growth of roots then nearly in all cases the CO_2 concentration in soil air was markedly exceeded in compacted soil and in several cases even severalfold.

Changes in the increase of CO_2 concentration occur even after the only passage of a heavy machine on the soil surface. These changes after the only passage of a machine were also proved by our measurements of the penetration resistance increase depending on the depth of a rut after the passage of forwarders on trial plots. As a rule, however, they do not reach critical values.

Present findings obtained at applications of the method of the CO_2 concentration measurement using the device chain mentioned above refer to a significant fact of the marked growth of CO_2 concentration in soil air on forest soils compacted by the passage of heavy machines (ie after repeated passages on skidding trails and at separate passages of machines through a stand). Thus, a restriction or even elimination of the function of part of the root system of trees can occur and, consequently, the loss of part of the active surface of a root zone. Method enlargement of air CO_2 concentration measurement and its use in terrain measurement confirm unambiguously hypothesis that heavy machines passages create worse permeable layer in surface layers of soil which restrict soil gases efflux to atmosphere. This is proving both markedly higher CO_2 concentration in soil air and markedly lower CO_2 concentration in air close to soil surface.

Thus, it is possible to deduce a fundamental recommendation for forest practice to attend strictly to the passage of heavy forest machines only along designed routes and exclude random machine passage anywhere in forest stand.

The method described above can be recommended for follow-up research into unfavourable impacts of the passage of heavy machines on roots of spruce because increased concentrations of CO_2 in soil compacted by heavy machines indicates changes occurred in the soil, provides and records necessary data (CO_2 concentration, temperature) in actual form and as a time series.

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