Lesn. Cas. For. J. 62 (2016) 23–28 DE GRUYTER OPEN DOI: 10.1515/forj-2016-0003

Lesnícky časopis - Forestry Journal
http://www.nlcsk.sk/fj/

PÔVODNÁ PRÁCA – ORIGINAL PAPER

Changes of carbon dioxide concentration in soils caused by forestry machine traffic

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Abstract

Forestry machine traffic causes a number of changes that are not immediately reflected in morphological changes of surface soil. These changes are physical and chemical in nature. The change in subsurface soil CO_2 concentration was one of the parameters of interest. The critical CO_2 concentration is thought to fluctuate around 0.6%. The primary objective of this paper was to determine the impact of forestry machine traffic on subsurface soil CO_2 concentration. We measured CO_2 concentration in the areas undisturbed by machinery and in the ruts in skid trails in eight forest stands. The measurements were performed using a Vaisala MI 70 meter. The results confirmed significant differences in gas concentrations between the individual measurement sites. In the ruts of the skid trails, CO_2 concentrations fluctuated in a range of 0.5 to 2.81% and significantly exceeded the critical concentration. Moisture content and bulk density had a significant impact on the change in gas concentration beneath the surface, which was confirmed by multivariate analysis of variance that revealed that the values of the coefficient of correlation fluctuated in a range of 0.39 to 0.74

Key words: CO_2 concentration; soil disturbance; cut-to-length machines; skidders

Editor: Bohdan Konôpka

Introduction

Soil respiration is one of the most important elements of carbon circulation in forest ecosystems (Hashimoto et al. 2004). Measurements of CO_2 concentrations have been used as proxy for root and microbial activity in soil (Nay et al. 1994). Soil respiration is the result of microbial respiration and the release of CO_2 through plant roots, which may account for 20 – 50% of all CO_2 released from the soil (Bouwmann & Germon 1998). Exact quantification of CO_2 content in soil is problematic, as it is one of the most variable soil parameters; the coefficient of variation may fluctuate between 30 – 150% (Stoyan 2000).

CO_2 released from the soil exhibits daily and seasonal fluctuations and is affected to a significant degree by environmental factors, such as soil moisture content and temperature (Davidson et al. 1998; Howard et al. 1993; Xu & Qi 2001). This effect varies depending on the type of ecosystem. Soil temperature is the primary and decisive factor in respiration in Boreal forests, while instantaneous moisture content only has a minimal effect (Schlentner & van Cleve 1984; Goulden et al. 1998; Rayment & Jarvis 2000; Morén & Lindroth 2000).

Temperature and humidity significantly influence soil respiration in forests of the temperate zone. Soil respiration stops, or is reduced, in the winter months, when temperature decreases and increases when temperature increases during summer (Dong et al. 1998; Fang et al. 1998; Londo et al. 1999; Ohashi et al. 1999). Soil type also significantly affects soil respiration. Large differences exist between fine grained and coarse grained soils and wet or dry soils (Schatschabel et al. 1984). CO_2 concentration in soil reflects biological activity because high concentrations of this gas negatively influence plant growth (Burton et al. 1997). Soil respiration is a major source of CO_2 in terrestrial ecosystems (Schimel 1995).

Soil organisms play a very important role in circulating substances, including CO_2, in terrestrial ecosystems (Paul & Clark 1989; Killham 1994; Roy et al. 1996; Sanders 1996).

Many studies, focused on CO_2 concentration in soil surface layers, are insufficient in terms of providing a correct explanation for CO_2 production in the soil, as the concentration of this gas differs in particular layers as a result of different physical, chemical and biological conditions (Hirano & Kim 2003).

Soil compaction changes the porous system in soil by reducing macro pores. Changes in porosity significantly influence air and water balance in soil, critical for plant growth (Gebauer et al. 2012). Air is a gaseous component of the soil and exists in pores that are not filled with water. It contains less oxygen and more CO_2 (from 0.5 – 5% and higher) compared to atmospheric air (Hillel 1998). Increased levels of CO_2 can be attributed to the root system respiration and the decomposition of organic material in soil. Soils with high CO_2 content and low oxygen content are poorly aerated, which may cause anaerobic conditions to occur (Hillel 1998).

Forest harvesting leads to compaction of surface soil layers, closure of the porous space and a decrease in the exchange of gases between the soil and the atmosphere. Forestry machine traffic may result in a decrease in available freely circulating substances (O_2) or their accumulation (CO_2) in the long term. Root growth may halt as a result of aeration problems. This condition intensifies in soils with

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higher clay content. This lead to greater focus on the soil CO_2 content caused by machine traffic and subsequent effect of forestry machine traffic on the root systems of trees. The use and practicability of this method was described by Neruda et al. (2010) and Skoupý (2011) for example. If CO_2 concentration reaches 0.6%, root growth in soil is significantly affected (Güldner 2002; Gebauer et al. 2012). Other authors, such as Erler and Güldner (2002) state that 1% is the threshold for normal soil recovery. If this threshold is breached, microbial activity is severely constrained and biological recovery takes longer. When CO_2 reaches 2%, all biological activity is halted and soil recovery happens only after physical agents are involved.

Our objective is to identify whether passages of forest harvesting machines cause a build-up of CO_2 in forest soils so severe that microbial activity or root growth is affected in the vicinity of skid trails. Our hypothesis is that CO_2 levels in the disturbed areas are higher than in the undisturbed areas of forest stands. Knowing that CO_2 content in soil air is a highly variable characteristic, we also set a hypothesis that moisture content and bulk density significantly affect CO_2 concentration in soil.

2. Materials and Methods

Measurements were conducted in eight forest stands. Stands n. 2027, 2051, 2052, 187C20, 188, 588, and 574B11 were located in Slovakia and stand n. 805J13 was located in the Czech Republic. Forest stands were different in tree species mix, soil conditions, and various types of harvests were carried out in them by different types of machines (cut-to-length machines – CTL, and skidders). Detailed characteristics of these stands are shown in Table 1. Measurements were conducted from July 2012 to August 2013.

Vaisala MI 70 device was used to measure the CO_2 content in soil. The device was equipped with two Carbocap GMP-70 probes with a measurement range of 0 – 5% CO_2 concentration. Vaisala HMP75B probe with measurement range for relative humidity of 0 to100% and temperatures of −20 to +60 °C was used to measure current air temperature and relative humidity in soil. Measured data was recorded directly onto the device's memory, from which the data was imported into a computer using the Vaisala MI 70 software.

Given that multiple variables concerning soil disturbance and the damage to the parent stand were observed simultaneously, the data were collected using sample plots evenly distributed across the entire stands (Fig. 1a). Dimensions of the sample plots were 20 × 20 m in stands where CTL machines operated (stands n. 2052, 2027, 188, and 187C20), or 20 × 40 m where skidders operated (stands n. 2051, and 588). Square sample plots were chosen for stands where cut-to-length machines operated, because the reach of the harvester's boom enables efficient work up to 10 m to each side. Rectangle sample plots were chosen in stands where skidders operated, because the reach of the winching cable was approximately 20 m to each side. Lukáč (2005) stated that the size of the statistical sample should be sufficient when the sample plots cover 10% of the total area of the stand in stands up to 50,000 m^2 and 5% of the total stand area in stands larger than 50,000 m^2. Within each sample plot we measured soil disturbance on two opposing sides in the direction of skidding.

Stands n. 574B11 and 805J13 were clear-cut, so there was no need to establish sample plots. In these stands we employed the measurement site sampling method as described by Schürger (2012). The measurement sites were located on skid trails with spacing of 5 m (Fig. 1b).

Measurements in the individual stands were conducted throughout the whole day. A total of 256 measurements were performed in all stands. CO_2 concentrations were measured using two Carbocap GMP-70 probes at the same time in: (i) rut of the skid trails; (ii) the undisturbed stand (control measurements). Soil air temperature and relative humidity in soil were entered into the meter before CO_2 was measured in order to regard for changing ambient conditions during the day. CO_2 concentration was measured in the surface soil layer in maximum 10 cm depth. The measurement procedure consisted of multiple steps that were conducted in sequence in order to maximize the accuracy of the CO_2 readings. First, approximately 12 cm deep openings with 2 cm diameter were

Table 1. Basic information on the forest stands where measurements were conducted.

Stand	GPS	Number of measurements	Stand size [ha]	Machine	Volume of harvest [m^3]	Type of harvest	Soil type
2052	48°40'37.95"N 18°5'41.25"E	40	7.9	JDH[a] + JDF[b]	265.87	T>50[i]	luvisol
2027	48°41'19.48"N 18°5'38.19"E	40	8.58	JDH[a] + JDF[b]	232.62	T>50[i]	40% luvisol 60% stagnosol
2051	48°41'9.31"N 18°4'57.79"E	20	16.7	ZTR[c]	95.4	T>50[i]	luvisol
187C20	48°58'6.31"N 18°39'15.40"E	24	5.89	NSS[d] + NVT[e]	90	T<50[j]	rendzic leptosol
188	48°58'5.55"N 18°39'24.47"E	44	12.52	NSS[d] + NVT[e]	190	T<50[j]	rendzic leptosol
574B11	48°35'25.84"N 19°2'41.66"E	44	1.59	HSM[f]	411.3	CC[k]	95% cambisol 5% luvisol
588	48°34'59.62"N 19°3'16.79"E	24	4.12	HSM[f]	215.24	POR[l]	40% cambisol 60% luvisol
805J13	49°49'59.69"N 14°46'25.71"E	20	2.72	PSH[g] + PSF[h]	96.6	CC[k]	modal cambisol

[a]JDH – John Deere 1070D; [b]JDF – John Deere 810D; [c]ZTR – Zetor 7245; [d]NSS – Neusson 132 HVT; [e]NVT – Novotny LVS5; [f]HSM – Hohenloher Spezial-Maschinenbau 805HD; [g]PSH – Ponsse Ergo 6W; [h]PSF – Ponsse Buffalo; [i]T>50 – thinning over 50 years of age; [j]T<50 – thinning under 50 years of age; [k]CC – clear-cut; [l]POR – partial overstory removal.

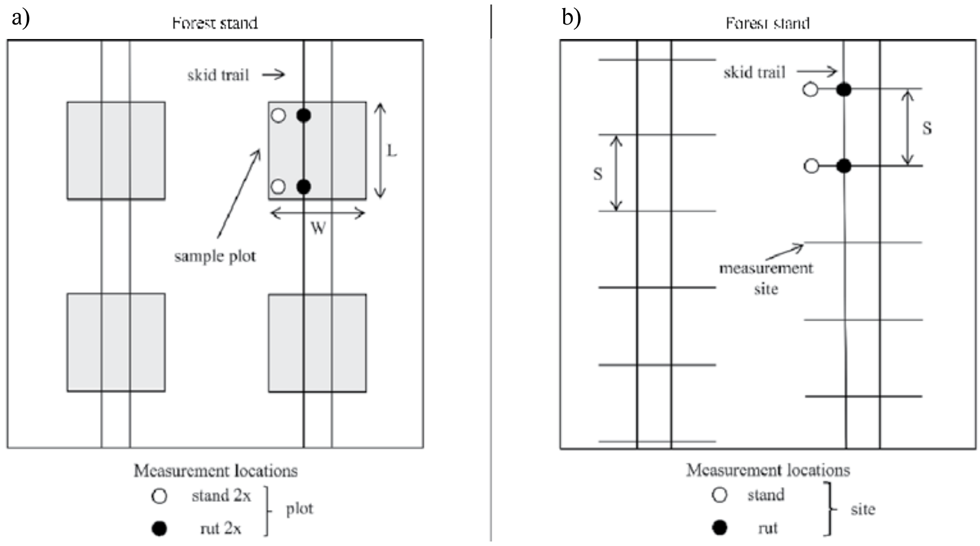

Fig. 1. Layout of the sample plot method of data collection (a) and the measurement site data collection method (b); L – length of the sample plot (20 m); W – width of the sample plot (20 m for cut-to-length machines, 40 m for skidders); S – spacing between two neighboring measurement sites (5 m).

drilled into the soil, then the probes were inserted into the opening so that the top part of the probes with diameter of 2.6 cm would seal the opening. After this, the probes were left in the soil for approximately three to five minutes without recording data into the device's memory so that the ambient air in soil would settle into its original composition (Vaisala 2012a,b). After the interval, the readings were recorded into the device's memory and the probes were taken out of the pre-drilled openings.

Along with CO_2, bulk density and soil moisture content were measured on nearby spots (cca five to ten centimetres away from the CO_2 measurement location) through gravimetric sampling. Soil samples were collected using a set of Eijkelkamp sealable sampling cylinders (volume 100 cm^3, length 50 mm, outer diameter 53 mm). The cylinder was inserted into the soil until it was completely filled with soil, removed from the soil, soil overhanging the cylinder was cut off, and the cylinder was sealed to avoid loss of moisture. Samples were then weighed in laboratory conditions on calibrated laboratory scales with an accuracy of 0.1 g and dried at a temperature of 105 °C for 24 hours, in order to determine the mass of the dry samples. Moisture content at the time of measurement was calculated according to Hraško et al. (1962):

$$w\ \% = \frac{m_v - m_s}{m_s} * 100 \qquad [1]$$

$w\,\%$ – relative soil moisture content [%],
m_v – weight of the raw soil sample [g],
m_s – weight of the dried soil sample [g].

Bulk density and moisture content were used to determine the strength of the relationship between them and the CO_2 concentration.

Before the statistical evaluation we sorted the data according to the forest stands from which they originated. The number of valid cases (number of measurements) in each stand depended on the total area of the stand (Table 1). First, we checked the normality of data through Shapiro-Wilk's test. Subsequently we proceeded to evaluate whether differences between CO_2 content in soil, bulk density of soil, and moisture content in the ruts of the skid trails and the control measurements in the undisturbed stand were statistically significant. We also tested the statistical significance of differences between data from particular stands. Data were evaluated through multivariate analysis of variance (MANOVA) for each stand individually. After testing the significance of differences between the data from individual locations and stands, we tested the relationship between CO_2 content (dependent variable) and bulk density of soil and moisture content (independent variables) through multivariate regression and correlation analysis separately for each forest stand. In this case we also tested the normality of residuals from the model through Shapiro-Wilk's test.

3. Results

Results of this study showed that CO_2 concentration in soil was considerably higher in areas disturbed by machine traffic (i.e. ruts) (Table 2). Fig. 2 illustrates this fact as it depicts the average CO_2 concentration in undisturbed stand soil and in soil from the ruts created by forestry machines. The figure depicts that compressed soil was unable to release excessive CO_2 through its surface into the atmosphere, which lead to the accumulation of CO_2 in the soil. The fluctuations in CO_2 concentrations in ruts indicate that soil compaction and soil moisture content as variables influencing the CO_2 accumulation were not homogenous and varied from one measurement site to another. CO_2 concentrations in ruts exceeded the concentrations from the reference measurement locations, i.e. the undisturbed stand, in all cases.

The overall mean difference in CO_2 concentration between the undisturbed stand and the skid trail rut locations was 0.91% (a relatively large difference). The smallest difference between locations was 0.28% CO_2 content while the largest was 2.22% CO_2 content. The minimum gas con-

Table 2. Changes in CO_2 concentration, bulk density and moisture content in individual stands and in the undisturbed stand and ruts of the skid trail measurement locations.

Stand	2052	2027	805J13	187C20	188	2051	574B11	588
CO_2 concentration [%] stand	0.59	0.72	0.34	0.24	0.28	0.58	0.59	0.30
CO_2 concentration [%] rut	2.81	1.84	0.74	0.52	1.51	1.19	1.73	0.57
Difference in CO_2 [%]	2.22	1.12	0.4	0.28	1.23	0.61	1.14	0.27
Bulk density g cm^{-3} stand	1.21	1.09	1.32	1.05	1.07	0.95	1.43	1.16
Bulk density g cm^{-3} rut	1.64	1.71	1.54	1.34	1.52	1.24	1.79	1.56
Difference in bulk density g cm^{-3}	0.43	0.62	0.22	0.29	0.45	0.29	0.36	0.40
Moisture % stand	25.94	23.04	13.20	28.2	20.4	20.18	39.2	20.41
Moisture % rut	25.48	26.36	11.17	31.5	32.4	18.60	33.6	20.92

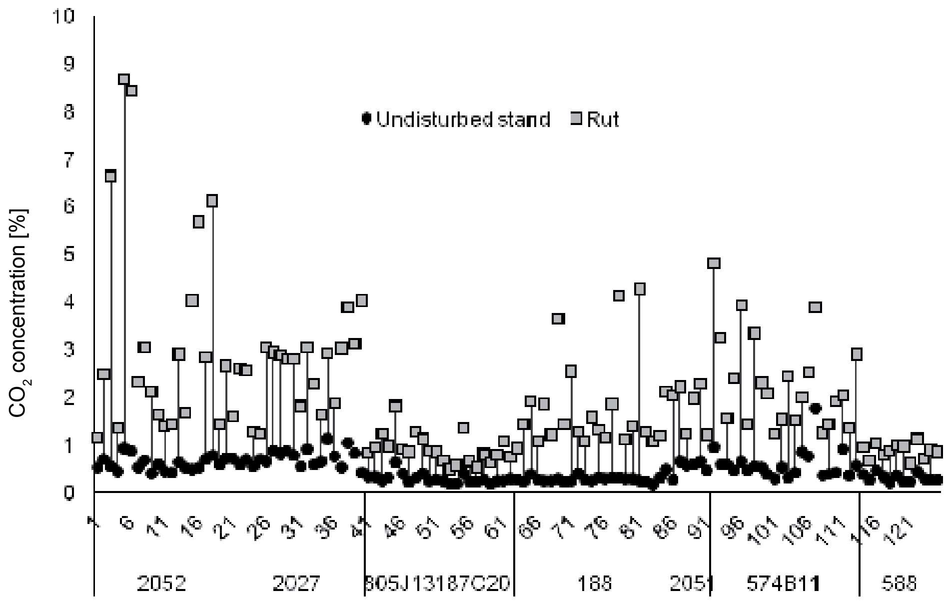

Fig. 2. CO_2 concentrations for each measurement in the undisturbed stand location and skid trail rut location; data from all measurements; vertical lines connect relevant data pairs.

centration in the undisturbed stand was 0.24% CO_2 while the maximum was 0.72% CO_2. Elevated concentrations were noted in the skid trail ruts in all cases, with a minimum value of 0.52% CO_2 and a maximum of 2.81% CO_2. The results from the ruts showed that the critical gas concentration level of 0.6% was exceeded in seven out of eight forest stands. Concentrations in individual stands fluctuated significantly (Fig. 3), which was caused partially by the change of temperature at the time of measurement and partially by the change in natural conditions of the stands. Multiple regression and correlation analysis was used to study the relationship between CO_2 concentration (dependent variable), bulk density of soil, and soil moisture content (independent variables) at the place of CO_2 measurements.

Multiple regression and correlation analysis was conducted for the individual stands given that MANOVA confirmed significant differences between individual stands ($F = 5.26$; $p = 0.00$) and measurement locations (stand, rut) ($F = 32.11$; $p = 0.00$). The value of the correlation coefficient fluctuated in a range of 0.39 – 0.74 (Table 3), which was a moderately strong relationship. Soil bulk density exhibited a significant impact on the change in CO_2 concentration in five forest stands and instantaneous soil moisture content exhibited a significant influence only in one case. The data from all stands were merged into a single database in order to increase the size of the statistical sample; this data was then analysed in the same manner, but separately for the stand and the rut locations.

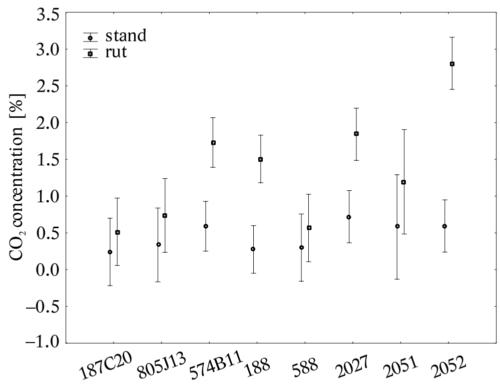

Fig. 3. Mean CO_2 concentration in individual stands for the undisturbed stand and ruts of the skid trails locations; vertical lines indicate 95% confidence intervals.

The results of multiple regression and correlation analysis measured between CO_2 concentration, bulk density of soil, and moisture content of soil in the undisturbed stand location (Table 4) showed a weak relationship with multiple R 0.30; R^2 0,09; $p < 0.003$, caused mainly by the variability of natural conditions. Soil moisture content influenced the

Table 3. Results of multiple regression and correlation analysis between CO_2 concentration, moisture content and soil bulk density in individual stands; Significance of variable: + yes, x no.

Stand	2052	2027	2051	187C20	188	574B11	588	805J13
Correlation coefficient	0.53	0.69	0.74	0.39	0.64	0.50	0.41	0.68
Moisture content	x	x	x	x	+	x	x	x
Bulk density	+	+	+	x	x	+	x	+

Table 4. Multiple regression and correlation analysis between the CO_2 concentration (dependent variable) bulk density of soil, and soil moisture content (independent variables), statistically significant values are marked bold; US – undisturbed stand location, STR – skid trail rut location.

N=125	b*	Std. error of b*	b	Std. error of b	t(122)	p-value
Abs. term			0.130443	0.125308	1.040982	0.299942
Bulk density us	0.121540	0.088211	0.001399	0.001015	1.377821	0.170781
Moisture us	**0.247732**	**0.088211**	**0.007027**	**0.002502**	**2.808386**	**0.005800**
Abs. term			−0.983991	0.940082	−1.04671	0.297303
Bulk density str	**0.233303**	**0.088154**	**0.013894**	**0.005250**	**2.64652**	**0.009205**
Moisture str	0.079206	0.088154	0.011587	0.012896	0.89849	0.370694

CO_2 concentration significantly in the undisturbed stand. Soil bulk density did not exhibit a statistically significant influence on changes in CO_2 concentration.

Multiple regression and correlation analysis of the values from the skid trail ruts showed a similarly weak relationship, with multiple R 0.24; R^2 0.06; $p < 0.03$ (Table 4). An important finding in this case is that soil bulk density exhibited a statistically significant effect on changes in CO_2 concentration in soil. Moisture content in this case did not exhibit a significant influence.

4. Discussion

The results of our measurements confirmed that CO_2 concentrations in compacted soil are higher than in undisturbed soil and that the critical gas concentration value of 0.6% was exceeded in practically all stands in skid trail ruts. The gas concentration fluctuated in a range of 0.28 – 0.72% in the undisturbed stand, compared to 0.52 – 2.81% in the ruts of the skid trail. Gebauer et al. (2012) reached similar conclusions in their work stating that the critical value is exceeded in nearly all skid trails exposed to forestry machine traffic a number of times over (1.2 – 3.4% CO_2 in CTL ruts compared to 0.4 – 0.5% CO_2 in the undisturbed stand).

Kuzyakov (2006) measured CO_2 content with soils compacted to three different densities, specifically: 1.1 g cm^{-3}, 1.3 g cm^{-3}, and 1.5 g cm^{-3}. Dry and wet conditions were examined for precipitation durations of 30 and 90 minutes. The results show a significant correlation between precipitation duration and CO_2 concentration in soil. According to his findings, CO_2 concentration is 42% higher with precipitation lasting 30 minutes and up to 53% higher with precipitation lasing 90 minutes. He found a significant correlation between soil compaction and CO_2. Soil compacted to 1.5 g cm^{-3} retains 32% more CO_2 compared to soil compacted to 1.1 g cm^{-3}.

CO_2 concentration measurements in soil confirm the increase in the content of CO_2 in the soil air as a result of disturbance caused by the heavy forestry machine traffic along skid lines, even if the effects of such forestry machine traffic are not visually apparent (Skoupý 2011). Neruda et al. (2010) confirm a distinct increase in CO_2 concentration on skid trails as a result of a single movement of such forestry machines.

5. Conclusion

One of the drawbacks of measuring CO_2 content in the soil is that it does not provide objective information on to the actual extent of disturbance caused by forestry machine traffic over the soil surface and the fact that CO_2 concentration is unstable and changes depending on natural conditions (time of year, temperature and, as statistically confirmed in our case, humidity and bulk density).

The results of our measurements and the measurements of many foreign authors confirm the hypothesis that forestry machine traffic creates less permeable layers in top soil layers, which hinders gas exchange between the soil and the atmosphere. This was confirmed by the results of our measurements, which correspond to the conclusions of other authors. Changes in gas concentrations are visible after the first passage of forestry machines over soil surface and their negative impact on tree root systems is proven.

Based on these facts, a number of basic recommendations can be determined for forest operations. The most important of these is that the forest managers should restrict movements of the forestry machines to skid trails and prevent any uncontrolled traffic through the stand itself.

Acknowledgements

This paper was elaborated as a part of scientific grant project VEGA - 1/0678/14 "Optimization of technological, technical, economic and biological principles of energy dendromass production".

References

Bouwman, A. F., Germon, J. C., 1998: Special Issue – Soils and climate change – Introduction. Biology ana Fertility of Soils, 27:219.

Burton, A. J., Zogg, G. P., Pregitzer, K. S., Zak, D. R., 1997: Effect of measurement CO_2 concentration on sugar maple root respiration. Tree Physiology, 17:421–427.

Davidson, E. A., Belk, E., Boone, R. D., 1998: Soil moisture and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest, Global Change Biolog., 4:217–227.

Dong, Y., Scharffe, D., Lobert, J. M., Crutzen, P. J., Sanhueza, E., 1998: Fluxes of CO_2, CH_4 and N_2O from a temperate forest soil: the effects of leaves and humus layers. Tellus 50B, p. 243–252.

Fang, C., Moncrieff, J. B., Gholz, H. L., Clark, K. L., 1998: Soil CO_2 efflux and its spatial variation in a Florida slash pine plantation. Plant and Soil, 205:135–146.

Gebauer, R., Neruda, J., Ulrich, R., Martinkova, M., 2012: Soil Compaction – Impact of Harvesters' and Forwarders' Passages on Plant Growt. In: Julio, J. Diez (ed.): Sustainable Forest Management - Current Research, Rijeka, CRO, InTec,. Available at: http://www.intechopen.com/books/sustainable-forest-management-current-research/impact-of-heavymachines-on-the-soil-root-system-and-plant-growth.

Goulden, M. L., Wofsy, S. C., Harden, J. W., Trumbore, S. E., Crill, P. M., Gower, S. T. et al., 1998: Sensitivity of boreal forest carbon balance to soil thaw. Science, 279:214–217.

Güldner, O., 2002: Untersuchungen zu Bodenveränderungen durch die Holzernte in Sachsen und Entwicklung eines Konzepts zur ökologisch verträglichen Feinerschliessung von Waldbeständen. In: Tagungsbericht der Sektion Forsttechnik des Verbandes Deutscher Forstlicher Versuchsanstalten, Sopron, Hungary, 10 p.

Hashimoto, S., Nobuaki, T., Suzuki, M., Inoue, A., Takizawa, H., Kosaka, I. et al., 2004: Soil respiration and soil CO_2 concentration in a tropical forest, Thailand. Journal of Forest Research, 9:75–79.

Hillel, D., 1998: Environmental Soil Physics. San Diego, CA, Academac Press, 771A.

Hirano, T., Kim, H., 2003: Long-term half-hourly measurement of soil CO_2 concentration and soil respiration in a temperate deciduous forest. Journal of Geophysical Research 108/D20: 4631.

Howard, D. M., Howard, P. J. A., 1993: Relationships between CO_2 evolution, moisture content and temperature for a range of soil types. Soil Biology. Biochemistr., 25:1537–1546.

Hraško, J., Červenka, L., Facek Z., Komár, J., Němeček, J., Pospíšil, F. et al., 1962: Rozbory pôd. Bratislava, Slovenské vydavateľstvo pôdohospodárskej literatúry, 342 p.

Killham, K., 1994: Soil. Ecology. Cambridge, Cambridge University Press, 242 p.

Kuzyakov, Y., 2006: Sources of CO_2 efflux from soil and review of partitioning methods Soil Biology & Biochemistr, 38:425–448.

Morén, A.–S., Lindroth, A., 2000: CO_2 exchange at the floor of a boreal forest. Agricultural and Forest Meteorology, 101:1–14.

Lukáč, T., 2005: Viacoperačné stroje v lesnom hospodárstve. Zvolen, Vydavateľstvo Technickej univerzity vo Zvolene, 137 p.

Londo, A. J., Messina, M. G., Schoenholtz, S. H., 1999: Forest harvesting effects on soil temperature, moisture, and respiration in a Bottomland hardwood forest. Soil Science Society of America Journal, 63:637–644.

Nay, M., Mattson, K. G., Bormann, B. T., 1994: Biases of Chamber Methods for Measuring Soil CO_2 Efflux Demonstrated with a Laboratory Apparatus. Ecology, 78:2460–2463.

Neruda, J., Kadlec, J., Ulrich, R., Cudzik, A, 2010: Soil Carbon dioxide concentration and efflux changes in ruts after heavy machine passes, FORMEC 2010 Forest Engineering: Meeting the Needs of the Society and the Environment July 11 – 14, 2010, Padova – Italy Proceedings.

Ohashi, M., Gyokusen, K., Saito, A., 1999: Measurement of carbon dioxide evolution from a Japanese cedar (*Cryptomeria japonica* D. Don) forest floor using an open-flow chamber method. Forest Ecology and Management, 123:105–114.

Paul, E. A., Clark, F. E., 1989: Soil microbiology and Biochemistry. San Diego, CA, Academic Press, 273 p.

Rayment, M. B., Jarvis, P. G., 2000: Temporal and spatial variation of soil CO_2 efflux in a Canadian boreal forest. Soil Biology & Biochemistry, 32:35–45.

Roy, J., Guillerm, J.–L., Navos, M.–L., Dhillion, S., 1996: Responses to elevated CO_2 in Mediterranean old – field microcosms: species community, and ecosystem components. In: Carbon Dioxide, Populations and Communities, London, Academic Press, p. 128–138.

Sanders, I. R., 1996: Plant-fungal interactions in a CO_2-rich world. In: Carbon Dioxide, Populations and Communities, London, Academic Press, p. 266–272.

Schachtschabel, P., Blume, H.-P., Hartage, K.-H., Schwertmann, U., 1984: Lehrbuch der Bodenkunde, Stuttgart, Enke, 394 p.

Schlentner, R. E., Van Cleve K., 1984: Relationships between CO_2 evolution from soil, substrate temperature, and substrate moisture in four mature forest types in interior Alaska. Canadian Journal of Forestry Research, 15:97–106.

Schimel, D. S., 1995: Terrestrial ecosystems and the carbon cycle. Global Change Biology, 1:77–91.

Schürger, J., 2012: Zhodnotenie negatívneho vplyvu traktorových technológií na pôdu v lanovkových terénoch. Zvolen, Dizertačná práca, 198 p.

Skoupý, A., 2011: Multikriteriálni hodnocení technologií pro soustřeďování dříví. Kostelec nad Černými lesy, Lesnická práce, 212 p.

Stoyan, H., 2000: Spatial heterogeneity of soil respiration and related properties at the plant scale. Plant and soil, 222:203–214.

Vaisala Oyj, 2012a: User's guide Vaisala Carbocap ® Hand-Held Carbon Dioxide Meter GM70. Helsinki, Vaisala Oyj, 68 p.

Vaisala Oyj, 2012b: Vaisala Application Note: How to measure CO_2? Helsinki, Vaisala Oyj, 4 p.

Xu, M., Qi, Y., 2001: Soil-surface CO_2 efflux and its spatial and temporal variations in a young ponderosa pine plantation in northern California, Global Change Biology, 7:667– 677.