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SOIL COMPACTION AND CHANGES IN CO_2 CONTENT IN FOREST STAND SOIL CAUSED BY PASSAGE OF SKIDDING TECHNOLOGY

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Abstract

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The paper was aimed on reforming on damage to soil caused by passage of universal wheeled tractors and forest wheeled tractors. We focused mainly on determining the changes in CO_2 content in soil after its compaction in comparison with unimpaired soil from the stand. We carried out the measurements in municipal forests of Stará Turá, in four stands, where a regeneration felling was done. We acquired data on the depth of ruts through the method of transversal profiles took samples of soil from the ruts and unimpaired stand to determine the bulk density and moisture content. We determined the content of CO_2 in stand and ruts with a Vaisala MI70 device. We selected the stands so that they would be uniform in age, terrain incline, terrain, and soil type. All of the stands had a low bearing sub – soils – flysch sandstone. This affected the rut depth after both machines passage. Rut depth indicated severe damage to the stand soil. We also observed severe differences in CO_2 content of the compacted soil. Measurements in all of the stands showed a significant increase in CO_2 content after its compression. Unimpaired soil reaches volume of 0.3% and rut soil reaches 1.8%. The compressed soils contained 6x the CO_2 of uncompressed soils. The results of statistical analysis show, that moisture content affects the CO_2 content more than bulk density. Coeficients of correlation between CO_2 and moisture content were r = 0.68 and 0.52 and between CO_2 and balk density were r = 0.26 and 0.36. Increase in moisture content causes CO_2 accumulation. Combined effects of these two characteristics are significant and show very strong correlation. There was for example r = 0.83 and independent characteristics influenced dependent on 69%.
From the outcomes the measurements we can state, that the passage of mechanisms causes significant changes in the stand soil.

Keywords: soil compaction, damage to soil, rut depth, CO_2 content

1 INTRODUCTION

Practice shows, that mobile technologies trough economic effectiveness to forestry. On the other hand they have various negative ecological effects. One of their negative effects is the degradation of forest stand soil. Increasing mass of the machines effects the soil in such manner, that the changes in its parameters is many times irreversible. The changes affects the water and air mode in the soil profile which decreases the biological activity of soils. We can say that changes in soil parameters caused by machinery passage decreases the ecological and productive stability of soil.

Mobile logging technology moves through unconsolidated terrains during its effective operation. The movement is restricted by various inner and outer factors. Inner factors include the parameters of each machine-engine performance, mode of transmission of the power from the engine to wheels, chassis type, weight of the load, etc. Outer factors include site conditions, physical characteristics of the soil, terrain incline, obstacles, type and age of the stand, climatic conditions, number of passes of the machine, etc. (Ferenčík *et al.*, 2008).

Soil compaction in a process caused by static and dynamic effects of contact pressure created by the propulsion systems of the logging technology and other sources. The effect of mechanism passage has to be studied not only from the view of pressure created by the mechanism, but also the frequency of passes of the mechanisms during the year, horizontal division of passes, speed of passes and slipping of propulsion systems e.g. (wheels or tracks) (Skoupý *et al.*, 2011). The deformation is caused by 1. slipping force, 2. compression and 3. combination of both (Dexter, 1973).

Another negative effect of mechanism passage is the creation of ruts of various depth. During the movement of mechanisms and high pressure their propulsion systems create the elasticity limit is exceed and plastic deformation occurs. Ruts are created (Koreň *et al.*, 2002).

European forestry does not have a consistent regulation of evaluation of the state of forest stands after the logging process was carried out. To determine the damage to the stand and its soil multiple methods are used. Their practicality, elaborateness and promptness varies. The most common methods are: Finnish, German and McMahon. Jiroušek *et al.* (2008) elaborated statistical tests of said methods. After reviving all of the methods they found out, that all of the methods are similar in their, accuracy and where selecting an appropriate method one should take economics into account and select the cheapest and least time consuming method.

Soil respiration is a result of microbial respiration and CO_2 expenditure by the roots of plants. The root CO_2 expenditure can be up to 20–50% of all CO_2 released into soil (Bowmann, Germon, 1998). Its exact quantification is very problematic, due to the fact, that CO_2 content is one of the most variable soil characteristics and its coefficient of variation can vary from 30–150% based on the conditions of the environment (Stoyan *et al.*, 2000).

Loss in macropores in soils decreases water and gas infiltration. Concentration of oxigen decreases and CO_2 concentration increases, eventually it can reach levels when it becomes poisonous which is unfavourable for the root systems of vegetation (Kuzyakov, 2006).

Movement of forestry machinery leads to soil compaction which causes structural changes of the soil mainly decrease in porosity and aerial capacity. These changes consequently lead to decreased availability of water, oxygen, nutrients and other substances or on the contrary their excessive accumulation. Soil is a significant source of CO_2 which is created directly in it and is subsequently released into the environment. Soil compression significantly decreases ventilation of soil. This information lead to presumption, that CO_2 can be cumulated excessively under compressed soil. Compressed soil can created a low permeable or impermeable zone which retends CO_2 in soil (Skoupý *et al.*, 2011). This hypothesis was further elaborated by Neruda *et al.* (2010) who focused mainly on the passage of heavy forwarders on forwarding lines. They measured the CO_2 content with a Vaisala with infrared probes capable of measuring the CO_2 in soil and on its surface. Other methods were based on using a CARBOCAP GMT 221 from Vaisala with basic measurement range of 3% and accuracy of 0.2%. The hypothesis set by (Neruda *et al.*, 2010) proved to be right. Their measurement showed significant increase in CO_2 concentration in soil compacted by passage of mechanisms. Their method was expended by measuring CO_2 emissions from the soil surface to the atmosphere in 2009–2010. The results also proved the hypothesis that the emissions from ruts are lower than emissions from unimpaired stand soil (Skoupý *et al.*, 2011).

2 MATERIAL AND METHODS

We carried out the measurements at the municipal forests of Stará Turá, managed by LESOTUR, s. r. o. (LLC.) in four stands – n. 75 and 100, where an UWT worked, and 87 and 102, where a FWT worked. Regeneration felling was carried out in each stand. We selected the stands, so that they would be similar in the following:

- soil type
- terrain type
- terrain incline
- average steam volume

The analysis of soil damage was based on determining the depth of ruts, CO_2 content in the stand and in ruts, collection of soil samples from ruts and from unimpaired stand soil for laboratory testing.

2.1 Measuring range

The data required for the research was collected on sites. The sites were created so that they would characterize the stand in all observed characteristics. Their count depended on the size of the stand and was determined from a nomogram (Ulrich *et al.*, 2002).

2.2 Depth of ruts

We determined the depth of ruts through the method of transversal profiles (Kindernay, 2010). We evaluated the intensity of mechanical damage to soil according to the Weise (2002) classification (Tab. V).

2.3 CO_2 content in soil

We measured the CO_2 content in soil with Vaisala MI70 device. We used two CARBOCAP GMP 70 probes one of which we placed into the rut and the other into the unimpaired stand soil. The measuring range was 0–5%. We set the measurement duration of 30 seconds over a five minute interval.

I: *Information on the forest stands where the UWT operated (municipal forests Stará Turá 2012–2021)*

Stand	Stand n. 75	Stand n. 100
Area [ha]	9.04	7.36
Age [year]	105	125
Orientation	E	SW
Incline [%]	35	25
Terrain type	04	04
Skidding distance [m]	100	180
Species	BK, SM, SC	BK, SM, SC
Abundance [%]	BK 71, SM 22, SC 7	BK 97, SM 2, SC 1
Mean stem volume [m^3]	BK 2.19, SM 2.20	BK 2.19, SM 2.54, SC
Sub-soil	Flysch sandstone	Flysch sandstone
Soil type	cambisoil	cambisoil

BK = *beech*, SM = *spruce*, SC = *larch*

II: *Information on the forest stands where the FWT operated (municipal forests Stará Turá 2012–2021)*

Stand	Stand n. 87	Stand n. 102
Area [ha]	3,09	8,89
Age [year]	125	125
Orientation	E	SW
Incline [%]	30	25
Terrain type	04	04
Skidding distance [m]	400	200
Species	BK, SM	BK, SM
Abundance [%]	BK 66, SM 34	BK 99, SM 1
Mean steam volume [m^3]	BK 2.19, SM 2.54	BK 2.56, SM 2.37
Sub-soil	Flysch sandstone	Flysch sandstone
Soil type	cambisoil	cambisoil

BK = *beech*, SM = *spruce*

III: *Technical parameters of LKT 81 T and Zetor 7245*

Machine Parameters	LKT 81 T	Zetor 7245
Dimensions w/l/h [mm]	2484x5700x2780	2260x4530x2780
Weight [kg]	6900	3985
Engine-type	DS 8004	Z 7201
Engine power [kW/rpm]	74/2200	46/2200
Maximum speed [km/h]	25	25
Maximum tractive force [kN]	80	90

IV: *Tyre type*

	tyre profile	Dimensions (in)	tyre width (cm)
FWT	sagittal	16.9 x 30	42.9
UWT	sagittal	Front wheels : 11.2 x 24 Back wheels : 16.9 x 30	28.4 42.9

2.4 Bulk density and soil moisture content determination

We collected the samples for bulk density and soil moisture content on every research site with Eijelkamp cylinders of 10^5 mm^3 (100 ml) volume. We collected two samples on every site – one from the rut and the other from stand. We determined the mass of humid sample and in dry state after 24 hours of drying at 105 °C.

V: *Mechanical damage of soil (Weise, 2002 in Schűrger, 2010)*

Level of soil damage	Rut depth (cm)	Damage characteristic
1. No damage	**0**	Soil with unimpaired vegetation and top humus layer.
2. Very light damage	**0**	Humus layer partially removed (<50%) or mixed with humus soil horizon. Soil is without any visible signs of compression. Soil cover damaged.
3. Light damage	**< 7**	The humus layer removed. Humus horizon partially (< 50%) removed. Soil compressed by machinery passage in low precipitation conditions. Bearing capacity unimpaired.
4. Moderate damage	**8–15**	Top soil horizon removed partially (50–80%). Soil compressed, water permeability decreased significantly. Visible lateral soil displacement near ruts.
5. Heavy damage	**16–25**	Mineral soil partially removed. Soil compressed or destructed by the tires, laterally displaced. Low to very low water permeability of soil. Water stays on the surface of ruts.
6. Very heavy damage	**≥ 26**	Mineral horizon uncovered. Very deep ruts, soil in ruts impermeable to water.

3 RESULTS

3.1 Depth of ruts

Since we collected data via establishing research sites, we calculated the average rut profile from all of the measured profiles on sites in particular stands. To evaluate the damage we always selected the maximal depth in the average profile (Tab. VI).

According to (Tab. VI) the level of damage in stands n. 75, 100, 102 was heavy damaged (level 5). In stand n. 87 the soil was moderately damaged (level 4).

VI: *Depth of track*

Stand	Rut depth (cm)
75	17
100	17
87	8
102	18

3.2 Comparasion of mean values of bulk density, moisture content and CO_2 content in compressed rut soil and soil in individual stands

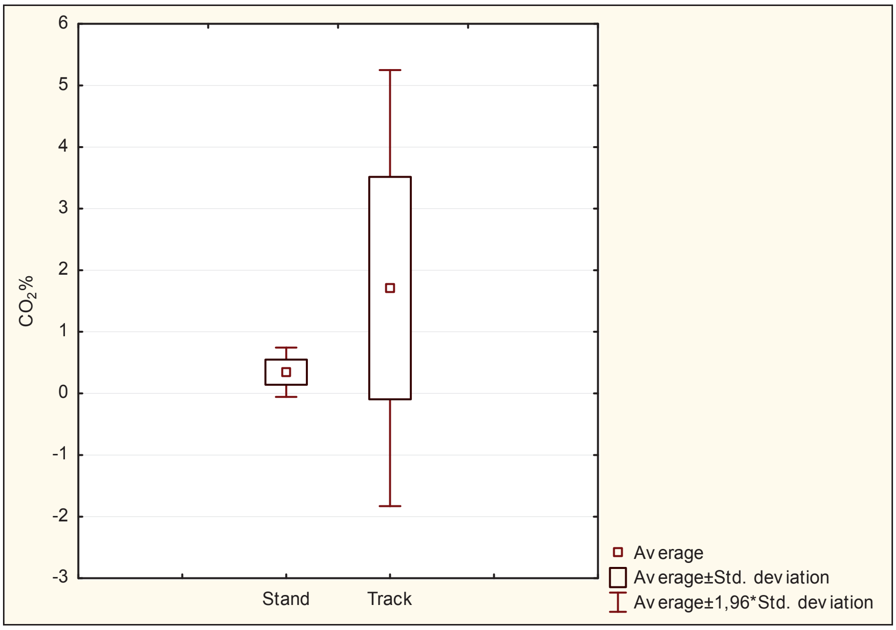
To evaluate the differences of CO_2 content in the stand and in the ruts we used a box chart. We constructed the chart from all values in all stands (Fig. 1).

According to Fig. 1 we can state, that CO_2 accumulates in compressed soil. Unimpaired soil reaches volume of 0.3% and rut soil reaches 1.8%. After compression the CO_2 content increased six times. The unimpaired soil has stable CO_2 content which can be seed from the variability of the values.

Marginal value of tolerable CO_2 content (0.6%) known from literature was surpassed. Values greater than this are unfavorable for the root system which, because of CO_2 accumulation, becomes inactive or its activity is decreased significantly (Skoupý *et al.*, 2011).

VII: *Mean values in individual stands*

Stand n. 75	**Bulk density (g.cm⁻³)**	**moisture content (%)**	**CO_2 (%)**
stand	0.72	14.66	0.25
rut	0.88	34.36	2.59
difference	0.16	19.7	2.34
Stand n. 100	**Bulk density (g.cm⁻³)**	**moisture content (%)**	**CO_2 (%)**
stand	0.85	19.39	0.51
rut	1.11	19.39	1.42
differece	0.26	0	0.91
Stand n. 87	**Bulk density (g.cm⁻³)**	**moisture content (%)**	**CO_2 (%)**
stand	1.05	18.77	0.35
rut	1.20	23.85	1.40
difference	0.15	5.08	1.05
Stand n. 102	**Bulk density (g.cm⁻³)**	**moisture content (%)**	**CO_2 (%)**
stand	0.92	20.15	0.28
rut	1.18	28.38	1.29
difference	0.26	8.23	1.01

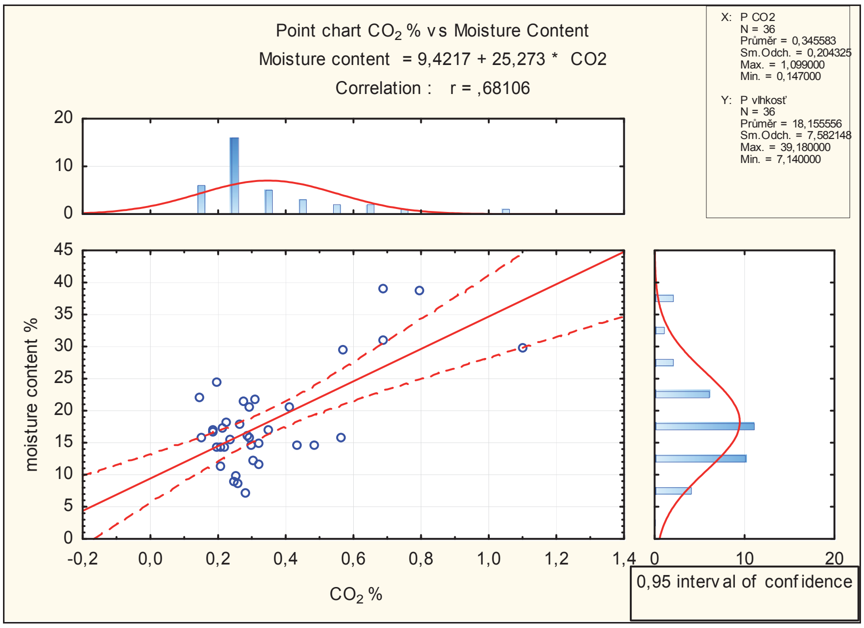


1: *Comparasion of CO_2 content in ruts and unimpaired stand soil*

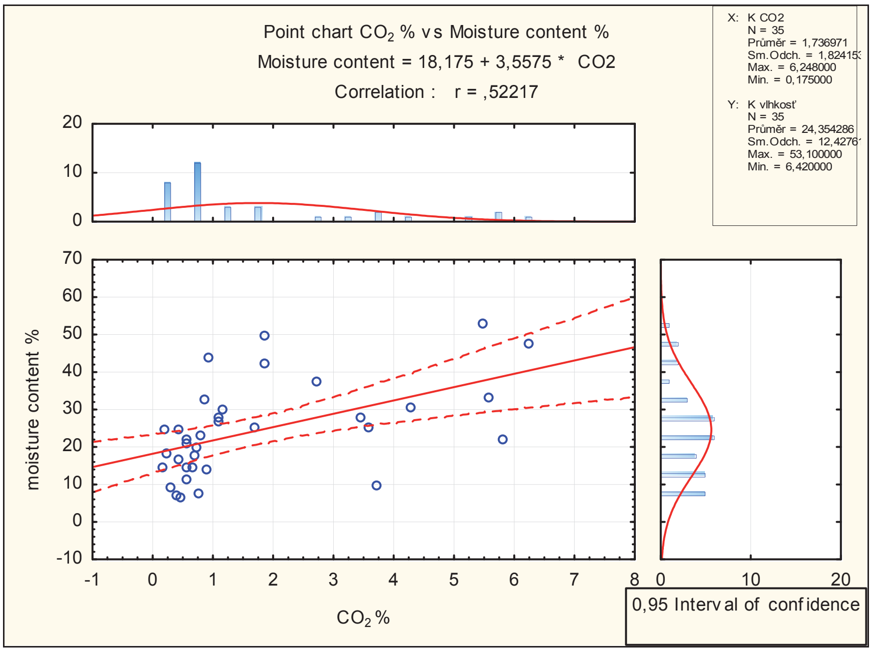
In other research we focused on other soil characteristics and their effect on CO_2 content. We observed the effects of soil moisture content and bulk density on CO_2 content. We used regression and correlation analysis to determine their effect. At first we examined the effect of moisture content on CO_2 content in unimpaired stand soil (Fig. 2) and subsequently in compressed ruts (Fig. 3). We then examined the effect of bulk density on CO_2 content in unimpaired soil (Fig. 4) and in ruts (Fig. 5).

Correlation was found between moisture content and CO_2 in unimpaired soil. Coeficient of corelation was r = 0.68 (Fig. 2). Correlation was found in ruts too (Fig. 3). The coeficient of correlation was r = 0.52. Increase of moisture content causes increase in CO_2 content. Soils with higher moisture content (e.g. after rainfall) can therefore show higher CO_2 content, which has to be allowed for in CO_2 measurements.

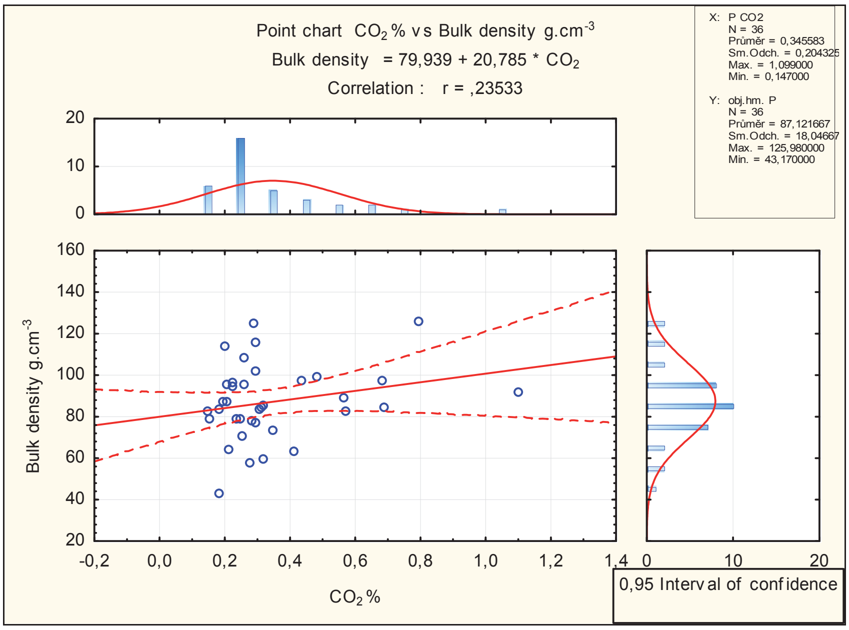
The correlation between bulk density and CO_2 content is weak. It can be seen in (Fig. 4), with r = 0.23. Bulk density has little influence on CO_2 content. In compressed soil r = –0.36 (Fig. 5), so increase in bulk density causes decrease in CO_2 content. The values were highly variable.



2: *Correlation between CO_2 content and moisture content – unimpaired soil*



3: *Correlation between CO_2 content and moisture content – ruts*



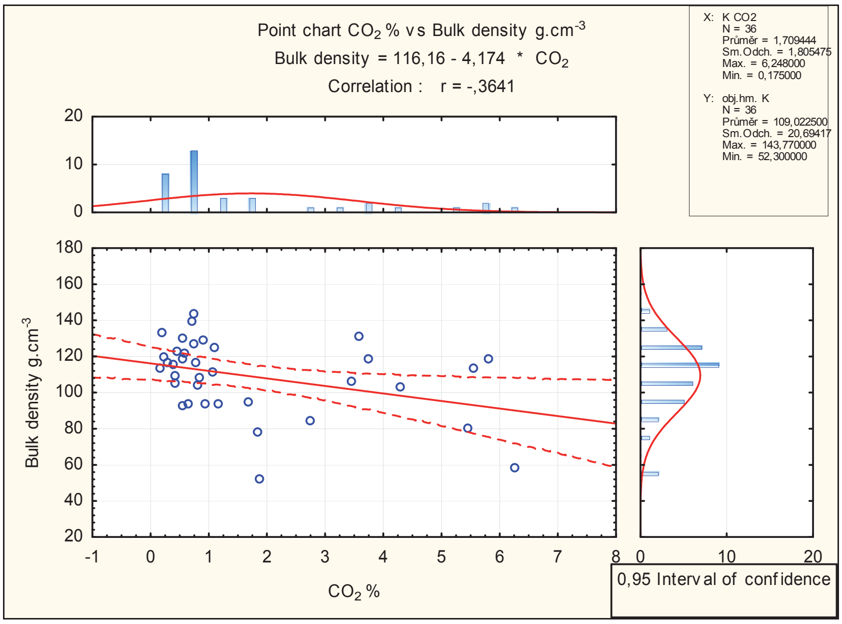
4: *Correlation between CO_2 content and bulk density – unimpaired soil*

We carried out a multicritetial statistical analysis of the effect both characteristics have on the CO_2 content for each stand.

Tab. VIII shows moderate dependence, with r = 0.44. It also shows that 19.7% of the variability of the dependet variable is caused by the variability of both independent variable.

According to our analysis the correlation is even stronger in ruts, with r = 0.6. 36.9% of the variability of the dependent variable is caused by the variability of the independent variables.

Multicriterial statistical analysis proved there is a strong correlation between bulk density, moisture content and CO_2 content (Tab. X). The coeficient of correlation shows very strong relationship (r = 0.85). The variability of the independent variables explains 72.8% of the variability of the dependent variable. The analysis of data from ruts (Tab. XI) shows a very strong relation r = 0.83. 69% of the variability of the dependent variable is explained by the variability of the independent variables. The joint effect of bulk density and moisture content on CO_2 content is greather than their individual effect.



5: *Correlation between CO_2 content and bulk density – ruts*

VIII: *Multicriterial correlation of CO_2 content, bulk density and moisture content in unimpaired stand soil (stand n. 75)*

Results of regression with dependent variable CO_2 % in stand R= 0.443; R^2 = 0.197; Adaption R^2 = -----						
F(2.7) = 0.858; p < 0.463						
Standard deviation of estimate = 0.09						
N = 10	**b***	**Standard deviation of b***	**b**	**Standard deviation of b**	**t(7)**	**p**
Absolute term			0.04	0.24	0.15	0.90
Bulk density (g)	0.47	0.38	0.003	0.002	1.26	0.25
Moisture content (%)	0.08	0.38	0.002	0.009	0.22	0.83

IX: *Multicriterial correlation of CO_2 content, bulk density and moisture content in ruts (stand n. 75)*

Results of regression with dependent variable CO_2 % in ruts R= 0.607; R^2 = 0.369; Adaption R^2 = 0.189						
F(2.7) = 2.052; p < 0.198						
Standard deviation of estimate = 1.86						
N = 10	**b***	**Standard deviation of b***	**b**	**Standard deviation of b**	**t(7)**	**p**
Absolute term			0.15	7.18	0.02	0.98
Bulk density (g)	–0.009	0.60	–0.0008	0.05	–0.02	1.00
Moisture content (%)	0.60	0.60	0.07	0.07	1.00	0.35

X: *Multicriterial correlation of CO_2 content, bulk density and moisture content in unimpaired stand soil (stand n. 100)*

Results of regression with dependent variable CO_2 % in stand R= 0.853; R^2 = 0.728; Adaption R^2 = 0.619						
F(2.5) = 6.7024; p < 0.038						
Standard deviation of estimate = 0.171						
N = 8	**b***	**Standard deviation of b***	**b**	**Standard deviation of b**	**t(7)**	**p**
Absolute term			–0.64	0.53	–1.21	0.28
Bulk density (g)	0.26	0.23	0.006	0.006	1.11	0.32
Moisture content (%)	**0.84**	**0.23**	**0.03**	**0.009**	**3.60**	**0.02**

XI: *Multicriterial correlation of CO_2 content, bulk density and moisture content in ruts (stand n. 100)*

N = 8	b*	Standard deviation of b*	b	Standard deviation of b	t(7)	p
Results of regression with dependent variable CO_2 % in ruts R= 0.830; R^2 = 0.690; Adaption R^2 = 0.566						
F(2.5) = 5.5652; p < 0.053						
Standard deviation of estimate = 0.86973						
Absolute term			–6.52	3.06	–2.13	0.09
Bulk density (g)	0.52	0.26	0.05	0.02	1.98	0.11
Moisture content (%)	**0.84**	**0.26**	**0.14**	**0.04**	**3.19**	**0.02**

XII: *Multicriterial correlation of CO_2 content, bulk density and moisture content in unimpaired stand soil (stand n. 87)*

N = 8	b*	Standard deviation of b*	b	Standard deviation of b	t(7)	p
Results of regression with dependent variable CO_2 % in stand R= 0.9756; R^2 = 0.951; Adaption R^2 = 0.932						
F(2.5) = 49.477; p < 0.0051						
Standard deviation of estimate = 0.04450						
Absolute term			0.29	0.12	2.31	0.07
Bulk density (g)	–0.19	0.1	–0.002	0.001	–1.90	0.12
Moisture content (%)	**0.93**	**0.1**	**0.01**	**0.001**	**9.33**	**0.0002**

XIII: *Multicriterial correlation of CO_2 content, bulk density and moisture content in ruts (stand n. 87)*

N = 8	b*	Standard deviation of b*	b	Standard deviation of b	t(7)	p
Results of regression with dependent variable CO_2 % in ruts R= 0.4702; R^2 = 0.2211; Adaption R^2 = ------						
F(2.5) = 0.70992; p < 0.0051						
Standard deviation of estimate = 1.7683						
Absolute term			–0.84	7.21	–0.12	0.91
Bulk density (g)	0.001	0.43	0.0001	0.05	0.002	1.00
Moisture content (%)	0.47	0.43	0.093	0.09	1.10	0.33

XIV: *Multicriterial correlation of CO_2 content, bulk density and moisture content in unimpaired stand soil (stand n. 102)*

N = 10	b*	Standard deviation of b*	b	Standard deviation of b	t(7)	p
Results of regression with dependent variable CO_2 % in stand R= 0.78132; R^2 = 0.6105; Adaption R^2 = 0.4992						
F(2.7) = 5.4860; p < 0.03688						
Standard deviation of estimate = 1.13187						
Absolute term			–0.17	0.26	–0.65	0.53
Bulk density (g)	0.14	0.35	0.001	0.004	0.38	0.71
Moisture content (%)	0.67	0.35	0.02	0.008	1.19	0.1

XV: *Multicriterial correlation of CO_2 content, bulk density and moisture content in ruts (stand n. 102)*

N = 10	b*	Standard deviation of b*	b	Standard deviation of b	t(7)	p
Results of regression with dependent variable CO_2 % in ruts R= 0.21955; R^2 = 0.0482; Adaption R^2 = -----						
F(2.7) = 0.17726; p < 0.8412						
Standard deviation of estimate = 0.20615						
Absolute term			–0.13	0.71	–0.18	0.86
Bulk density (g)	0.22	0.37	0.004	0.006	0.59	0.57
Moisture content (%)	0.008	0.37	0.00008	0.004	0.02	0.98

The coeficient of correlation is r = 0.47 and there is a strong relationship between CO_2 content, bulk density and moisture content.

The coeficient of correlation is r = 0.78 which means a very strong relation between the variables.

4 CONCLUSION

Our research proved, that both machines have severe negative effects on soil and are the source of a level 5. soil damage (Weisse, 2002). The severity of soil damage was partially influenced by the conditions in which the technologies worked. All of the stands were on low bearing soils (flysch) which deformas even in low humidities and small loading. From this point of view we have to take the conditions of the environment into account when considering suitable technology and the terms of its operation.

Measurements in all of the stands showed a significant increase in CO_2 content after its compression. Unimpaired soil reaches volume of 0.3% and rut soil reaches 1.8%. The compressed soils contained 6x the CO_2 of uncompressed soils. CO_2 accumulation in soils affected by forest machinery passage is evident.

This leads to recommendation for the praxis that movement of heavy machinery should be restricted only to dedicated skidding lines.

The results of statistical analysis show, that moisture content affects the CO_2 content more than bulk density. Coeficients of correlation between CO_2 and moisture content were r = 0.68 and 0.52 and between CO_2 and balk density were r = 0.26 and 0.36. Increase in moisture content causes CO_2 accumulation. When we carried out a multicriterial statistical analysis the CO_2 content this combined effects of these two characteristics are significant and show very strong correlation. There was for example r = 0.83 and independent characteristics influenced dependent on 69%.

The difference in soil damage is not significant, when we look at the machine used (forest wheeled tractors vs. universal wheeled tractors) so we cannot determine which machine is more harmful to soil. Forestry technology causes CO_2 accumulation in soil, but the CO_2 content is affected by various other factors which vary over time. The factors include footwall, soil texture, soil type, soil characteristics, temperature, moisture content, vegetation, characteristics of the technology. Based on the characteristics mentioned above we have to choose the most suitable technology which would minimize all negative effects on the forest stand soil and forest as a whole.

SUMMARY

The thesis is aimed on evaluating the soil damage caused by forest mechanization traffic – special forest tractors and universal tractors. The main goal was to determine the changes in the content of CO_2 in soil after compression and the causes of CO_2 increase under the compressed soil – identification of factors causing the increase. Measurements were carried out in four forest stands in the municipal forests of Stara Tura, in which regeneration exploitation was carried out. The stands were alike in age, terrain incline, terrain and soil type. The data on the depth of tracks was collected by means of transverse profile method, samples of soil from the stand and track were taken to determine the volumetric weight and moisture content. The differences in content between the stand and track were determined through a VAISALA MI70 device. The depth of tracks in both technologies reached grade 5 soil damage – heavy soil damage, which was caused partially by the location of the stands in the flysch area and have a low carrying capacity. The measurements confirmed significant differences between CO_2 content in unimpaired soil and compressed track soil. Measurements in all of the stands showed a significant increase in CO_2 content after its compression. The compressed soils contained 6x the CO_2 of uncompressed soils. Unimpaired soil reaches volume of 0,3% and rut soil reaches 1.8%. CO_2 accumulation in soils affected by forest machinery passage is evident. Volumetric weight and moisture content proved to be significant factors in CO_2 content variability, these factors were studied further in the STATISTICA 10.0 software. The results of statistical analysis show, that moisture content affects the CO_2 content more than bulk density. Coeficients of correlation between CO_2 and moisture content were r = 0.68 and 0.52 and between CO_2 and balk density were r = 0.26 and 0.36. Combined effects of these two characteristics are significant and show very strong correlation. There was for example r = 0.83 and independent characteristics influenced dependent on 69%. Higher levels of moisture content and volumetric weight were recorded in measurements of compressed track soil. Forest mechanization moving through the forest soil on the skidding trails causes measurable changes in soil characteristics.

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REFERENCES

BOWMAN, A. F., GERMON, J. C., 1998: Introduction. *Biology and Fertility of Soils*, 27: 219.

DEXTER, A. R., 1973: The response of unsaturated soils to insotropic stress. *Soil Sci.*, 4: 491–501.

FERENČÍK, M., MESSIGEROVÁ, V., STANOVSKÝ, M., 2008: Zhodnotenie dopadu harvesterovej technológie na lesnú pôdu v špecifických podmienkach oravského flyšu. In: *Użytkowanie maszyn rolnicnych i leśnych*, Zakopane.

JIROUŠEK, R., KLVAČ, R., LIŠKA, S., 2008: Kontrolní metody pro stanovení poškození půdy a stojacich stromů ťežebně dopravními technologiami. *Zprávy lesnického výzkumu*, 53, 4: 301–307.

KINDERNAY, D., 2010: *Stanovenie limitov ťažbovo-dopravnej erózie a poškodenia lesa na vybraných stanovištných podmienkach*, Dizertačná práca, Technická univerzita vo Zvolene, s. 141, LF 11116-2078.

KOREŇ, J., 2002: Prirodzená regenerácia vybraných druhov lesných pôd mechanicky poškodených pri približovaní dreva traktormi. In: *Logistika technickej výroby dreva v Karpatoch*, Zvolen: Technická univerzita vo Zvolene, 124–131. ISBN 80-228-1170-X.

KUZYAKOV, Y., 2006: Sources of CO_2 efflux from soil and review of partitioning methods. *Soil Biology and Biochemistry*, 38, 3: 425–448.

NERUDA, J., KADLEC, J., ULRICH, R., CUDZIK, A., 2010: Soil Carbon dioxide concentration and efflux changes in ruts after heavy machine passes. In: Proceeding of FORMEC 2010, Forest Engineering: *Meeting the Needs of the Society and the Environment. Padova, July 11–14.* Padova: Formec. ISBN/ISSN 978 88 6129 569 8.

SCHŰRGER, J., 2012: *Zhodnotenie negatívneho vplyvu traktorových technológií na pôdu v lanovkových terénoch,* Dizertačná práca, Technická univerzita vo Zvolene, s. 199, LF 11116 -2190.

ULRICH, R., SCHLAGHAMERSKÝ, A., ŠTOREK, V., 2002: *Použití harvesterové technologie v probírkách*, Brno: MLZU Brno, 97 s.

SKOUPÝ, A., BUCHAR, J., CIBULKA, M., HOLČÍKOVÁ, P., JANATA, P., KADLEC, J., KLIMÁNEK, M., KLVAČ, R., KOLAŘÍK, J., KULHAVÝ, J., LIŠKA, S., MENŠÍK, L., MIKITA, T., NERUDA, J., NEVRKLA, P., REJŠEK, K., SYNEK, M., ULRICH, R., VAVŘÍČEK, D., 2011: *Multikriteriální hodnocení technologií pro soustřeďování dříví*, Lesnická práce s. r. o., 211 pp. ISBN 978-80-7458-016-1.

STOYAN, H., 2000: Spetial heterogenity of soil respiration and related properties at the plant scale. *Plant and soil,* 222: 203–214.

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