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Damage Caused by Wheeled Skidders on Cambisols of Central Europe

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Abstract

Machine traffic and timber skidding significantly affect the soil surface and soil properties. The effects are mostly negative and result in soil erosion, worsening of soil properties and inhibition of the growth of roots and soil organisms. In this study, we evaluated forest soil damage caused by the HSM 805 HD wheeled skidder during timber skidding in selected forest stands in the School Forest Enterprise in Zvolen. We estimated the limits for operation of forest machines in the stands and evaluated the moisture content and bulk density of the soil, CO_2 concentration in the upper layer of the soil, determined the soil texture, Atterberg limits and critical moisture using the Proctor test, CBR test and examining the depth of ruts on skid trails. The measurements were taken from undisturbed forest soil unaffected by skidder traffic, the ruts and between the ruts.

The results showed significant differences between the values of soil samples from undisturbed soil and the soil affected by the skidder. The exceeding of CO_2 concentration limits and bulk density in the soil from the ruts were recorded in both stands. The methods used present the basic methodology for evaluating the effect of logging machinery on forest soil and for setting limits that will allow or prohibit the operation of logging machinery according to forest stand conditions. The moisture content of soil, when it changes from the solid to plastic phase, was chosen as the limit for machine operation. This value is also easy to measure.

Keywords: limits, soil damage, moisture, timber skidding

1. Introduction

Machinery used for timber skidding causes various damage to the remaining trees and forest soil. This damage is primarily caused by using machinery in unsuitable conditions, or by using unsuitable machines in given conditions. For example, using large skidders in the first thinning, or skidding timber after heavy rainfall usually cause damage far beyond any limits. Determination of the limits is the most important way to decrease the damage caused by skidders. Most methods evaluate the damage after the logging process is finished. Such methods are based on measurement of changes in soil properties caused by the machinery. The measured properties are usually penetration resistance, bulk density of soil, moisture content of soil and depth of ruts (Stanovský et al. 2012). Problems connected with the influence of skidding machinery on forest soil have been studied by many authors and connected with the rapid development of the machinery during the past 50–60 years (Ebel 2006). The negative influences of machinery on the soil surface has been researched by many authors including Hildebrand (1981), Hildebrand and Wiebel (1982), Benecke (1982), Bredberg and Wästerlund (1983), Löffler (1983), Becker et al. (1986), Löffler (1986), and Zander (1988).

The movement of forest machinery on the soil surface causes changes of its shape. The changes are dependent on soil moisture, its physical properties and other characteristics. These changes usually result in erosion of skid trails (relocation of upper soil horizons and structural changes of the soil). Mechanisation and modernisation of the logging process increase work costs with unchanged timber prices (Matthies et al. 1995, Hamberger 2002, Wehner 2002, Ziesak 2004). This results in a continued performance and dimensional growth of forest machinery (Forbrig 2000), especially the machinery weight. This is the most dangerous factor causing negative effects on forest stands after forest harvesting and timber transportation. The present paper focuses on skidders. In Slovakia more than 70% of harvested timber is transported from forest stands to forest landings by wheeled skidders.

Various authors, such as Löffler (1986), Becker et al. (1986), Hoffman and Becker (1990), came to the conclusion that even the first pass of heavy forest machinery on the surface of forest soil causes significant structural changes in its upper layers. There are many factors that affect the rate of soil damage after logging and only their detailed research will enable dealing with the damage. Soil moisture is one of the most important of them (Majnounian and Jourgholami 2013). Determination of critical moisture content in soil is crucial for devising the limits for using harvesting and transporting machinery in unfavourable conditions. Two basic limits of soil moisture content can be used in forestry practice:

⇒ Critical value of soil moisture for its compaction. Soil with moisture content at this level will be the most susceptible to compaction caused by forest machinery traffic;

⇒ In case of further increase of the soil moisture, at a certain point it will reach the second critical value – plastic limit. Creation of tracks in the soil starts at this very moment if forest machinery is used in such conditions.

It is necessary to implement soil protection into forestry certification systems, such as the Forest Stewardship Council (FSC) Programme for the Endorsement of Forest Certification (PEFC). Selecting the suitable technology and season for harvesting and timber skidding is the basis for minimising the impacts of technology on the forest environment.

The present study aimed to estimate simple limits for operation of the HSM 805 HD skidder in given conditions. These limits should be easy to measure/estimate for forestry practice without the need for special equipment. The next goal was to compare the properties of forest soil in the undisturbed forest stand and the soil in the skidding line to evaluate the level of damage caused by the operation of the HSM 805 HD wheeled skidder. We also assessed the efficiency of individual methods for forestry practice.

2. Material and methods

The measurements were carried out in two forest stands with similar conditions (slope, exposition, soil type, shelterwood system). Motormanual felling and skidding with the HSM 805 HD skidder took place in both stands. Basic data about the forest stands is presented in Table 1 and data about the skidder in Table 2.

Felling in the forest stands was conducted in different seasons. Forest stand 588 was felled in August 2012 during a dry period, when the total recorded precipitation in the given area was approx. 10 mm per month (SHMU 2012). The second forest stand 574 was felled in October 2012, during a period with intensive rainfall, when the total precipitation was almost 160 mm per month (SHMU 2012). The measurements in both stands were performed immediately after the

Table 1 Basic data about forest stands

Stand number	588	574B11
Place	VŠLP Zvolen LS Budča	VŠLP Zvolen LS Budča
GPS coordinates	48.58348387N 19.054429793E	48.590818386N 19.04499979E
Area, ha	4.1	1.6
Soil type	Cambisol	Cambisol
Soil texture	Silt loam	Sandy loam
Slope, %	25	20
Tree species*	DB 30%, BO 23%, HB 17%, BK 9%, JS 6%, SM 3%, CR 2%, OS 1%	BK 78%, BO 11%, DB 7%, HB 3%, CR 1%
Age, years	110	110
Felled volume, m^3	215	411
Treatment, m^{3}ha^{-1}	52	257
Treatment type	Seed cut	Overstory removal cut
Exposition	SV	SV
Felling time	August 2012	October 2012
Number of plots/ number of measuring lines	6/12	–/22 (spacing 15 m)

* DB – oak, BO – pine, HB – hornbeam, BK – beech, JS – ash, SM – spruce, CR – cherry

Table 2 Technical parameters of the HSM 805 HD skidder

Weight, kg	11 700 (including crane and grapple)
Tyre pressure, kPa	65 (Mellgreen 1980)
Engine	IVECO NEF
Displacement, cm^3	3908
Max. power/at revolutions, kW/n min^{-1}	110/2500
Max. torque/at revolutions, Nm/n min^{-1}	490/1400
Transmission	CLARK 2000; powershift, converter, 3+3 speeds, additional transmission (2 speeds)
Tyres	600/60–30.5
Axles	NAF
Winch	ADLER HY 20–double drum
Pulling force, kN	2x100
Winch speed, mmin^{-1}	0–150
Max. cable length/at diameter, m/mm	80/14
Crane	LOGLIFT F 101 RT 72
Reach, m	7.2
Gross lift torque, kNm	125
Net lift torque, kNm	98
Slewing torque, kNm	34

logging process to avoid changes to the soil properties. This work was based on the comparison of properties of undisturbed soil in the forest stands with properties of soil in the skid trails created during the logging process. The properties were only measured in newly created skid trails to avoid the influence of previous treatments. The intensity of traffic was described by means of treatment intensity (Table 1) and by the ground pressure of the machine (Table 2).

Determination of the sample size was conducted in two ways:

⇒ In stand 588 (after seed cut), we used square shaped sample plots due to the fact that we also recorded the damage of the remaining stand (not presented in this paper). The number of sample plots was determined on the basis of the Finnish method adjusted by Ulrich (2002). The sample plots (20x20 m) were set so that the centre of the plot was placed on the skidding line. Soil samples were collected from both opposite edges of the plots, which were transversal to the skidding lines (two measuring lines on one sample plot);

⇒ The residual stand in stand 574 was not present because an overstory removal cut was carried out. Therefore, data on the remaining stand was not recorded and it was not necessary to establish sample plots. Hence, we only established lines transversal to the skidding line. The number of lines was estimated on the basis of the equation for setting the minimal sample size according to Scheer (2010) and Schürger (2012).

In both cases, the measurements were carried out on established lines. Following methods were used:

⇒ measurement of moisture content and bulk density of the soil (by using the Eijkelkamp sampling cylinder set),

⇒ measurement of the CO_2 concentration in the upper layer of the soil, using the Vaisala MI70 device,

⇒ Proctor test (for determination of the critical moisture at which the soil is maximally compressible),

⇒ assessment of soil texture using the washing and densimetric method according to Casagrande,

⇒ determination of the plasticity index (Atterberg limits),

⇒ CBR test,

⇒ measurement of the transversal soil surface profile on skid trails (McMahon 1995).

For the determination of the soil moisture and bulk density, three soil samples were taken from each established line. One sample was taken from the soil in undisturbed forest, the second was from the rut, and the third was taken from between the ruts. The Eijkelkamp sampling set was used to take samples. The set contains cylinders with a capacity of 100 cm^3. We used the standard sampling procedure and took the sample after removing the upper organic layer of the soil. The samples were weighed (m_w) and we calculated the bulk density in the natural status. After this procedure, the samples were dried at 105°C, until they reached a constant weight – dry weight (m_0). Then, the moisture content of the samples was calculated (W_r) according to the following equation:

$$W_r = \frac{m_w - m_0}{m_0} \times 100, \% \qquad (1)$$

Where:

m_w weight of fresh sample, g;

m_0 weight of dry sample, g.

The calculated bulk densities of fresh soil from individual forest stands were compared with critical values. The critical bulk density values for individual soil types inhibiting the growth of roots were estimated according to Table 3.

Table 3 Critical soil bulk density values which inhibit the growth of roots (Arshad and Coen 1992) in Skoupy et al. (2011)

Soil type (texture)	Critical bulk density of soil, g cm^{-3}
Sand, loamy sand	1.80
Fine sands and loamy sands	1.77
Sandy loam	1.75
Loam, sandy clay loam	1.70
Clay loam	1.65
Sandy clay	1.60
Silt, silt loam	1.55
Silty clay loam	1.50
Silty clay	1.45
Clay	1.40

The concentration of CO_2 in soil was measured at two locations on the measuring line. One measurement point was in the rut and the other was placed in undisturbed forest soil. Both measurements were conducted at the same time using the VAISALA MI70 device connected with two identical probes. CO_2 measurement probes were placed close to the points where we took the soil samples. The distance of the CO_2 measuring points from the soil sampling points was as small as possible, but far enough to avoid mutual influence of the measurements (approx. 20 cm). Both probes were placed in previously drilled holes. The depth of the holes was 10 cm and the diameter was identical with the diameter of the probes. Gaps between the soil and the probe were sealed. The measuring range of both probes was between 0–5% CO_2 in the soil atmosphere. The device recorded the values every 15 s during a 5 min period in every sampling place. Original Vaisala software was used for processing the recorded data. The critical value of the CO_2 concentration in soil for the growth of roots and for the survival of soil microbiota is 0.6% (Güldner 2002).

We also determined the damage to the soil surface and measured the depth of the ruts from the undisturbed surface on the lines using the McMahon (1995) method. These measurements were carried out at the established lines, transversally to the skidding lines. One depth measurement was performed per every 20 cm of skid trail width. Damage levels were estimated according to Weise (2002) in Lukáč (2005).

For the evaluation of physical characteristics of the soils, two soil samples were taken from both forest stands. One sample was from the undisturbed forest stand and the other was from the rut. Washing and densimetric methods (Casagrande) were used for assessing the soil texture.

The standard Proctor test was used for the assessment of critical moisture content (for compaction) in the soil. The plastic limit of individual soils was estimated using the method described in detail by Poršinsky et al. (2006).

The mechanical strength of soil was estimated using the California bearing ratio (CBR) test. The principle of the test is based on pressing a steel cylinder with a diameter of 50 mm into the soil sample at a speed 1.27 mm min^{-1} and recording the pressure at depths of 2.54 mm and 5.08 mm. The recorded pressure was compared with the standardised pressure for the given depth and the final CBR values were estimated according to the following formula:

$$CBR = \frac{p}{p_s} \times 100, \% \tag{2}$$

Where:

p recorded cylinder pressure at given depth, kPa;

p_s standard pressure, 70.8 kPa at 2.54 mm and 106 kPa at 5.08 mm.

We tested the soil sample with the maximum moisture estimated in the Proctor test. A sample with increased moisture was tested after 96 hour saturation in water.

For processing and evaluating the collected data, we used the MS Excel, Statistica 10.0, EijkelkampPenetroViewer and Vaisala MI 70 software products.

3. Results

As presented in Table 4, we recorded a higher average moisture content of all soil samples taken from stand 574 when compared with stand 588. The average moisture of samples from the stand, rut and between the ruts in stand 588 was almost identical. In stand 574, we also recorded only minor changes in soil moisture.

Table 4 Average soil moisture values in forest stands

Stand		588	574
Average moisture of soil, %	Undisturbed	20.4	36.2
	In rut	20.9	33.6
	Between ruts	20.8	35.1

Fig. 1 shows significant differences in the bulk densities of soil samples from individual locations. The critical bulk density value (1.55 g cm^{-3} according to Table 3) in forest stand 588 (silt loam) was exceeded in the rut.

The average soil moisture content was approx. 21% (Table 4). The soil texture in forest stand 574 is sandy loam with the addition of gravel. The critical bulk density value for such soil type is 1.75 g cm^{-3} (Table 3). In this case, the average bulk density from the rut samples exceeded the critical value (1.79 g cm^{-3}) and the average bulk density of samples taken between ruts was 1.72 g cm^{-3}. The average soil moisture content in this stand ranged from 33–36%. The moisture content was considerably higher when compared with stand 588. The higher soil moisture content was caused by higher precipitation during skidding in stand 574.

We examined the differences between the mean bulk density values of individual soil samples from all of the localities (wet samples after sampling and the same samples after drying) from both stands. *t*-test was used for the validation of the statistical confidence of differences. Test results are presented in Tables 5 and 6. Significant differences are marked with +.

Table 5 Results of the *t*-test for mean bulk density values of samples from individual forest stands

Stand	Samples	Undisturbed vs. Rut	Undisturbed vs. Between ruts	Rut vs. Between ruts
588	Wet	+	+	-
	After drying	+	+	-
574	Wet	+	+	-
	After drying	+	+	-

Significant differences were recorded between the undisturbed soil samples against the rut samples as presented in Table 5. These differences proved to be present in all four cases (fresh and dried samples from both forest stands). Statistically significant difference was also found between the undisturbed soil samples and the samples taken from between the ruts. On the other hand, no statistically significant differences were found between the rut samples and the samples taken from between the ruts.

The differences were also tested between the mean dry sample values from individual forest stands. The results of the test are presented in Table 6.

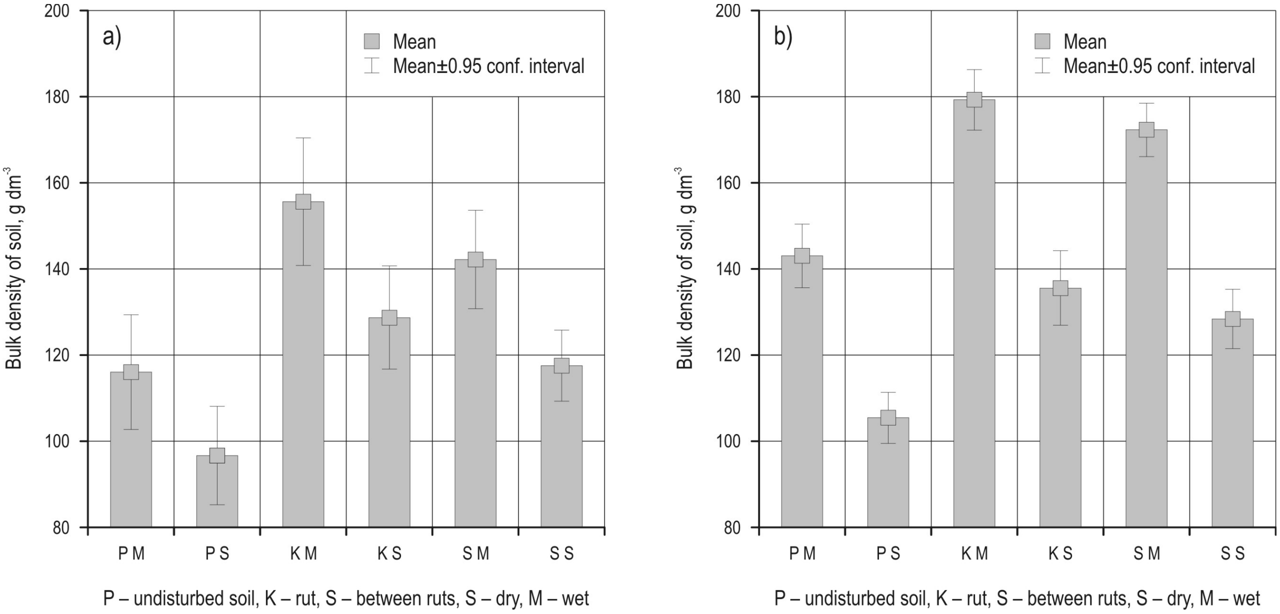

Fig. 1 Average bulk densities of soil samples from individual locations: a) stand 588, b) stand 574

Table 6 Results of the *t*-test for mean bulk density values of soil samples from both stands after drying

Dry samples	588 vs. 574
Samples from undisturbed soil	+
Samples from ruts	-
Samples between ruts	-

The difference between the average bulk soil densities taken from the undisturbed area in both forest stands was found to be statistically significant. On the other hand, no significant differences were recorded between the stands in the case of rut samples or samples taken from between the ruts. Therefore, it can be concluded that the soils in these stands (with different parameters) were compacted to similar bulk densities.

The measured CO_2 concentration values in the soil atmosphere from both stands are presented in Fig. 2.

A significant increase of CO_2 content was recorded in the ruts of both forest stands compared to the undisturbed soil values. In stand 588 the CO_2 level reached 190% of the value from the undisturbed soil (simultaneous measurements). CO_2 concentration in the rut almost reached the critical value (0.6%) in this stand. We observed a similar situation in the other stand (574), where the CO_2 level in the soil of the rut was 2.93 times higher than the level of the undisturbed soil. In this stand the CO_2 concentration in undisturbed soil was near critical, and the concentration in the rut exceeded the critical value 2.88 times. A comparison of values between the stands showed a significant difference in both values. The CO_2 concentration of the undisturbed soil from stand 574 was approx. 193% higher when compared with stand 588. A similar situation is seen between the values measured in ruts, where the increment was approx. 304%. These results show a significant increment of CO_2 concentration caused by machinery traffic in both forest stands. We also recorded a significant difference in the concentration between the undisturbed stands and the ruts. These differences were caused by an increase of precipitation during skidding in stand 574.

Analyses of soil properties was carried out to determine the critical soil moisture content values in both stands (Tables 7 and 8). When the soil moisture content reaches or exceeds the critical value, all machinery traffic in forest stands should be prohibited.

The soil texture in stand 588 was determined as silt loam. The technical standard STN 72 1002 assigns this soil into category VII, VIII, or IX; the most frequent soil particle was silt. These soils are prone to ground freezing, and after water saturation their load capacity drops by approx. 40% compared to soil in optimal conditions. The critical soil moisture value, which limits the use of technology, ranges within 31–33%. Intensive compaction of upper soil layers starts if the soil moisture reaches 24%.

According to our analyses, the soil in stand 574 is of the same type as the previous one and their properties are similar. The critical value for creation of ruts (plastic

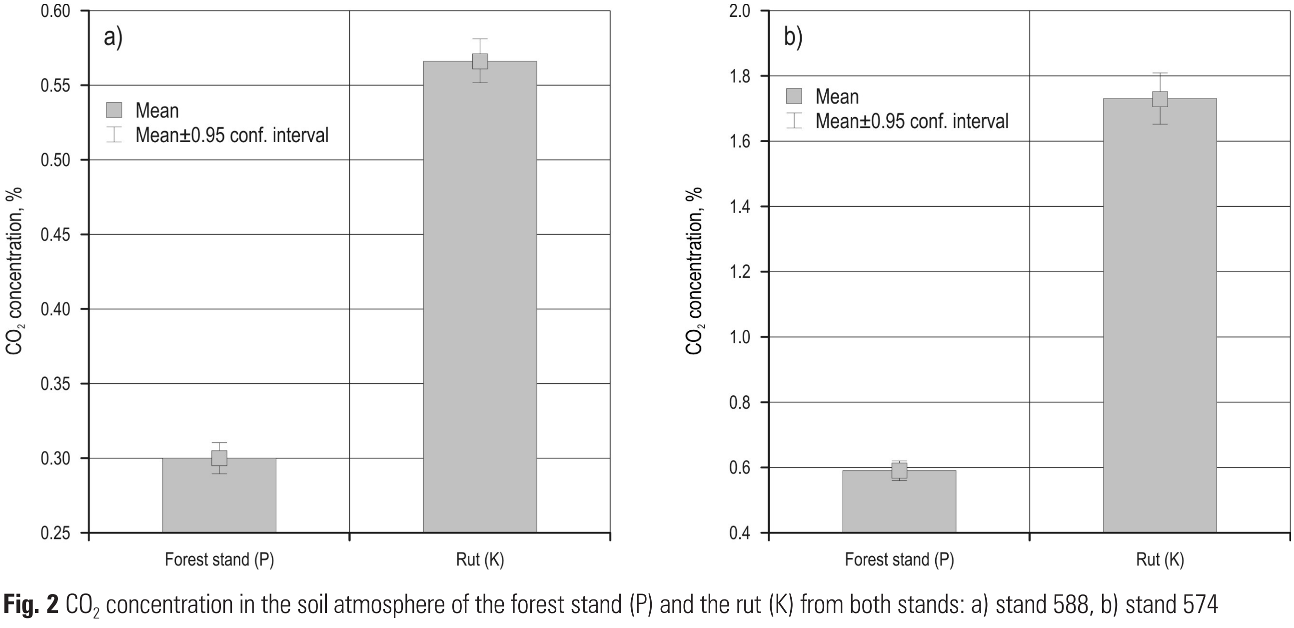

Fig. 2 CO_2 concentration in the soil atmosphere of the forest stand (P) and the rut (K) from both stands: a) stand 588, b) stand 574

Table 7 Soil texture and critical soil property values in stand 588

Soil texture		Silt loam	
Locality		Undisturbed stand	Rut
Particle size distribution %	Clay	5	5
	Silt	68	71
	Sand	27	24
Water content %	Liquid limit	44	42
	Plastic limit	31	33
	Max. compaction	24	31
Plasticity index		13	9

Table 8 Critical soil property values in stand 574

Soil texture		Silt loam	
Locality		Undisturbed stand	Rut
Particle size distribution %	Clay	18	11
	Silt	47	52
	Sand	35	37
Water content %	Liquid limit	43	35
	Plastic limit	30	23
	Max. compaction	22	22
Plasticity index		13	13

limit) for the previously undisturbed soil of the forest stands is different than the limit for previously compacted soil (ruts, skidding lines, forwarding lines, etc.). In this case it is 30% and 23%, respectively. The value for maximum soil compaction in this stand is 22%, both for the undisturbed soil and for the soil in ruts.

The load capacity of the soil was determined using the standard CBR test. Results of the test are presented in Tables 9 and 10. The test was divided into two parts. In the first part, we tested the samples adjusted to moisture, when the soil is mostly susceptible to compaction (optimum moisture). We individually determined the optimum moisture for every sample using the Proctor standard test (Tables 8 and 9). In the second part, we tested soil samples, which were previously saturated for 96 hours with water.

Table 9 Results of the CBR test samples from stand 588

Sample		Optimum moisture		After 96 hour of saturation	
		Undisturbed	Rut	Undisturbed	Rut
Moisture content, %		22.7	30.8	26.3	33.3
Bulk density, kg m^{-3}		1480	1340	1480	1370
Porosity, %		44.6	49.8	44.6	48.7
Saturation, %		75.4	82.7	87.5	93.7
CBR depth ratio % /Ncm^{-2}	2.54 mm	5.7/40	4.3/30	5.4/38	3.1/22
	5.08 mm	6.0/64	4.4/47	5.3/56	3.3/35

The soil penetration resistance from the undisturbed stand 588 (Table 9) with optimum moisture was 40 N cm^{-2} (CBR index 5.7%) at a depth of approx. 2.54 mm, and it increased to 64 N cm^{-2} (CBR index 6.0%) at a depth of approx. 5.08 mm. After the test, the sample was put into water for 96 hours. The test results after saturation were as follows: the moisture content increased and the soil penetration resistance decreased. At a depth of approx. 2.54 mm, a resistance of approx. 38 N cm^{-2} was recorded (CBR index 5.4%), and at a depth of approx. 5.08 mm the resistance was 56 N cm^{-2} (CBR index 5.3%).

Penetration resistance is lower in the case of soil samples from the rut. Table 10 presents the results of the CBR soil tests from forest stand 574. In this case, even the little change (increase) of soil moisture content, after saturation with water, caused a significant decrease of the soil penetration resistance. Penetration

Table 10 Results of CBR test samples from stand 574

Sample		Optimum moisture		After 96 hour of saturation	
		Undisturbed	Rut	Undisturbed	Rut
Moisture content, %		18.6	22.7	21.8	26.3
Bulk density, kg m^{-3}		1600	1480	1602	1480
Porosity, %		40.1	44.6	40.0	44.6
Saturation, %		74.3	75.4	87.2	87.5
CBR depth ratio %/ Ncm^{-2}	2.54 mm	8.9/63	5.7/40	4.3/30	5.4/38
	5.08 mm	9.5/107	6.0/64	3.8/40	5.3/56

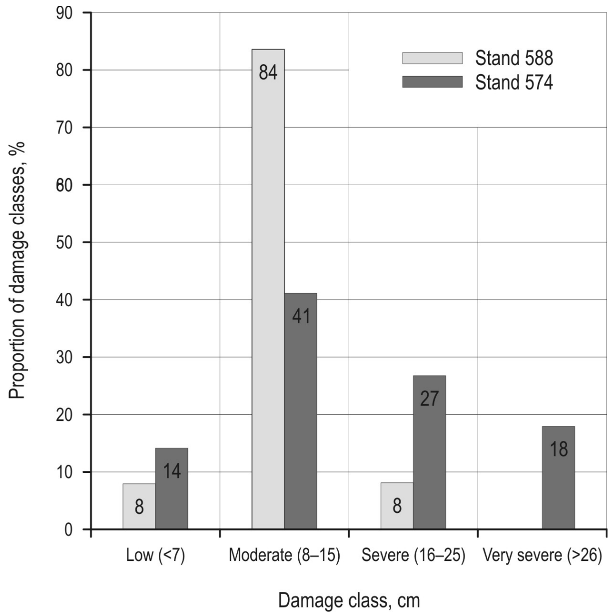

Fig. 3 Percentage of individual forest stand damage classes (classification according to Weise 2002)

resistance of the undisturbed stand sample adjusted to optimum moisture was 63 N cm^{-2} (CBR index 8.9%) at a depth of approx. 2.54 mm, and 101 N cm^{-2} (CBR 9.5%) at 5.08 mm. The penetration resistance of the soil sample after saturation decreased to 30 N cm^{-2} (CBR 4.3%) at a depth of 2.54 mm, and 40 N cm^{-2} (CBR 3.8%) at a depth of approx. 5.08 mm. Both optimum and saturated soil sample resistance from the rut were lower than the soil from the undisturbed stand.

The percentages of forest stand damage classes based on measured rut depths are presented in Fig. 3.

Significant differences in damage intensity were recorded in both stands. We determined that most of the ruts in stand 588 were in the moderate damage class. Only 8% of ruts with severe damage were recorded, and there were no ruts with very severe damage. In the second stand, 27% of ruts with severe and 18% with very severe damage classes were recorded, respectively. These results were affected by higher skidded volume in the second forest stand, and additionally the skidding process was conducted during the period with intensive rainfall. These results confirm the importance of carefully planning the skidding process with regard to climatic conditions and the requirement of determining the limits of soil damage.

4. Discussion

The bulk densities of fresh soils showed significant differences between the undisturbed forest stand and rut samples. In stand 588, the average bulk densities ranged from 1.16 g cm^{-3} (undisturbed stand) to 1.56 g cm^{-3} (rut). In stand 574, it was approx. 1.43 g cm^{-3} in the stand and approx. 1.79 g cm^{-3} in the rut. In both cases, a significant increase of soil bulk density was recorded as a result of soil compaction caused by skidder traffic, and the estimated soil bulk densities from ruts exceeded the critical values (Table 3) in both stands. Kindernay (2010) conducted research on cambisols in various parts of Slovakia after felling and timber transport made by a harvester and a forwarder. He determined the bulk density of rut soil at approx. 0.96 g cm^{-3}, which is equal to our soil bulk density from the natural forest stand. Rab (1992) states the bulk density of rut soil is approx. 1.12 g cm^{-3}, and Anderson et al. (1992) determined it to be 1.10 g cm^{-3}. In our case, the upper soil layers were compacted to a higher level.

The estimation of bulk density and its comparison with critical values (Table 3) is suitable for estimating soil damage levels after skidding. However, it is not applicable as a criterion for predicting future damage caused by machine operation in given conditions.

The measurements of the soil CO^2 concentration confirmed a significant increase in ruts after skidding compared to undisturbed forest stand soil. In stand 588, the CO_2 concentration was approx. 0.3% in undisturbed soil and 0.57% in the rut. In stand 574, it was approx. 0.56% and 1.73% in the rut. These results are similar to measurements conducted by Gebauer et al. (2012). They measured the soil CO_2 concentrations in forest stands after timber extraction and skidding with harvester technology. Their results show that the critical value (0.6%) was significantly exceeded in almost all cases after the passage of harvesters and forwarders, and in some cases the value was exceeded several times (e.g. 1.2% and 3.4% CO_2 in a harvester rut as opposed to 0.4% and 0.5% CO_2 on surfaces unaffected by harvesters). The lower values of CO_2 content in stand 588 were probably affected by the dry conditions during the measurements. The values from stand 574 were higher because they were taken during the wet season.

Measurement of the soil CO_2 concentration is also applicable as a method for assessing soil damage after mechanical operation, but not for determining whether the machine will cause unacceptable soil damage. This method requires a special measuring device, and the CO_2 content in the soil varies during the day and during the year (Hirano et al. 2003).

In our case, the soil was the most susceptible to compaction when its moisture content was, according to the Proctor standard test, between 24.3–31.0% in stand 588, and between 22.0–21.8% in stand 574.

After reaching the plastic limit, the soil changes its physical properties from the solid to plastic viscous phase, which has minimal bearing capacity even with the use of low pressure tyres, so skidder traffic on forest soil will create ruts on the skidding line. In our case, the moisture content, where the soil reached the plastic limit, was 31–33% for silt loam soil in stand 588 and 22–29% for silt loam soil from stand 574.

The actual soil moisture content in stand 588 was approx. 20.4 to 20.9%. The soil moisture content in this stand did not exceed the critical value. The moisture content of the soil from stand 574 was significantly higher than in stand 588. The critical value was exceeded in this case. The results of damage measurement (Fig. 3) show that, in the case of forest stand where the plastic limit was not exceeded, the damage is significantly lower than in stand 574, where the soil moisture exceeded the limit value. This difference was caused by heavy rainfall during skidding in stand 574.

The plastic limit of soil may be used in forestry practice as a simple criterion for the operation of forestry machinery in the skidding process. If the soil moisture content exceeds this limit, forest machines should cease operation until the moisture decreases below the set limit. The practical assessment of soil moisture content will require a moisture probe for measuring the actual moisture. For an easy and fast decision in the field, it is possible to use the »thread rolling method« (Persson 2013, Lüscher et al. 2009). For this test, it is necessary to take a small sample of the soil and try to roll it into a thin thread. The thinner and longer the thread, the higher the soil moisture capacity. If it is possible to roll the thread to a diameter of 3 mm before it starts to break into shorter pieces, the soil reached the plasticity limit (Klobouček et al. 1979).

5. Conclusion

It is impossible to choose an ideal logging technology that causes no damage to the forest soil and stand because of the high variability of environmental conditions in our forests. Despite this, it is the duty of the forest manager to choose optimal technology which causes minimal forest stand and soil damage. Exact and easily measurable limits for forest machinery will help in the decision-making process for given conditions. The limits will help to stop the operation of machinery under conditions where they would probably cause irreparable damage to the forest stand or soil and plan their operation during seasons with minimal rainfall.

Soil vulnerability depends on its texture, moisture content, the machine weight and its pressure on the soil surface. Soil moisture is one of the most important factors and is also easy to measure. We used the soil moisture content that changes the soil from the solid to plastic phase (plasticity limit) as the critical value for skidder operation. In our case, the critical values were approx. 31% in stand 588 and 30% in stand 574. If the soil moisture reaches its critical value, it is necessary to immediately stop the operation of forest machinery until the moisture content drops below the plasticity limit. Determination of such limits for various soil types (textures) enables easy determination of the suitability of conditions for the operation of machinery using a simple moisture probe.

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