

A comparison of methods to estimate harvest-induced damage to the soil using the example of a beech timber stand

Dariusz Kulak

University of Agriculture in Kraków, Faculty of Forestry, Department of Forest and Wood Utilization, Al. 29-Listopada 46,
31–425 Kraków, Poland.

Tel. +48 12 662 50 92, e-mail: rkulak@cyf-kr.edu.pl

Abstract. The study determines the extent of soil disturbances occurring during mechanised harvesting operations in a beech timber stand and investigates whether applying different research methods can be used to classify, in a comparable way, forest areas with different levels of soil damage. In the analysed stand, felling and on-side processing were conducted with chainsaws, while extraction – using a farm tractor. After the completion of logging operations, visible soil disturbances on each sample plot were measured, including surface area, volume and depth, and the value of five most common indicators of soil damage was calculated. The share of disturbed surface area, the volume of soil disturbances and different soil damage indicators allowed sample plots to be arranged in the same way according to increasing levels of soil damage occurring during harvesting. A different order was observed only in relation to the depth of the ruts formed. The similarity of the applied measures and classifications of soil disturbances indicates that all of the methods can be applied to make simple comparisons of the degree of soil damage. Because field trials are easy to perform, soil damage indicators based on a visual assessment of soil condition, without the need to take measurements, are worth recommending at first. A fuller picture of the level and nature of detected soil damage, however, can be obtained by taking into account the depth of the disturbance.

Key words: logging damage, indicator of soil damage, beech timber stand, agricultural tractor

1. Introduction

Currently, the evaluation of the impact of harvesting systems on the forest environment, particularly on the soil, should be one of the most important criteria of their selection. This is due to the fact that the improperly selected machines and harvesting systems not only lead to the degradation of the soil itself, but also, by changing its structure and water relations, have an adverse effect on the growth of both seedlings and older trees even decades after the performed operations (Wert, Thomas, 1981).

Therefore, it is crucial to recognise the size and characteristics of disturbance to the soil structure using different harvesting systems and work methods in as many

forest stands as possible, differing in species composition, stand characteristics, performed operations, topography and habitat conditions, treatment times, etc. However, as indicated by Porter (1997), studies related to the assessment of damage caused by timber extraction are lengthy and complicated methodically.

Among the various methods of measuring soil deformation caused by mechanised harvesting specified by Wästerlund (1992), such as measurement of soil compaction and permeability, root sampling to determine the severity of damage, the visual method should be considered the simplest. However, it is somewhat subjective and hard to compare with other methods. The more so, that the visual assessment of the soil condition is most often connected with the conversion of soil disturbance

class to digital indicators to enable an easier evaluation of the obtained results (Giefing, 1999; Gil 2003).

Another relatively simple method is measuring the surface area and volume of the ruts, often ending in the calculation of the overall indicator of the level of soil damage (Suwała 2000). In addition to the cognitive objectives, the main task of such research is to assess the impact of a given machine or harvesting system on individual components of the forest environment (Dudek, Sosnowski 2011). In this context, it is important that the various methods of assessing damage caused by harvesting allow obtaining comparable results.

The aim of this study was to assess the extent of disturbance in the soil surface layer in an upland beech stand after final cutting and skidding logs with a farm tractor using different damage assessment methods, and to verify whether the applied methods in a comparable way classify forest areas varying in intensity of damage caused by harvesting operations.

2. Methods

The studies were conducted in the territory of the Krzeszowice Forest District (Kraków RDSF) – 50,13°N, 19,63°E in a beech stand in which final cuts were performed in the cutting system II a. The basic characteristics of the analysed forest stand are shown in Table 1.

In the stand under review, 50 m × 50 m square sample plots with an area of 25 acres were established close to the three strip roads, at a distance of about a hundred metres from their exit, to assess ground damage caused by harvesting. The plots were marked with symbols A, B and C.

The logging operations were carried out during the summer. Trees were cut by loggers using chainsaws. The cut trees were bucked in such a way that after delimiting they were cut into two or three logs. The logs were dragged to the forest landing using a farm tractor. Bucking of the piled wood assortments from the top sections of trees was done directly on the landing. The skidding required that the tractor had, from time to time, to leave the strip road to attach the load.

Each sample plot was covered with a grid of squares with a side of 10 m. Its nodes were stabilised in the field with wooden poles. After the completion of the logging operations, measurements of visible soil disturbances were taken on each sample plot. The length, depth and width of each disturbance were measured every 0.5-m with an accuracy of up to 0.01 m using a tape measure. On this basis, the surface area and the volume of soil disturbances were determined for each sample plot. Also, the value of a synthetic indicator of soil damage

Table 1. Main characteristics of the studied stand

Species composition	9 beech 120
/ age	1 pine 120
Stocking	0.8
Canopy closure	broken
Volume [m ³ /ha ⁻¹]	420
Forest habitat type	upland deciduous forest
Site index	II
Medium height [m]	31
Medium DBH [cm]	42
Soil	rendzic leptosols, light loamy sand

Ug developed by Suwała (1999) was calculated, using the following formula:

$$Ug = G_{ko} + G_{bp} + 2 G_{bg} + G_{kp} \quad (1)$$

where Ug is a synthetic indicator of damage to the soil surface layer, G_{ko} is a percentage share of the volume of the ruts in the soil layer with a thickness of 10 cm, G_{bp} is a percentage share of the volume of the shallow furrows with an average depth of 5 cm in the soil layer with a thickness of 10 cm, G_{bg} is a percentage share of the volume of deep furrows with an average depth of more than 5 cm in the soil layer with a thickness of 10 cm, G_{kp} is a percentage share of the volume of hoof prints in the soil layer with a thickness of 10 cm, calculated on the basis of the empirical formula.

The above formula indicates that the depth of the furrows and ruts affects only to a limited extent the value of the Ug indicator, because the ruts deeper than 10 cm do not increase its value. This results from the assumption adopted by the author of the indicator that changes in this soil layer are the most important because it contains most conductive tree roots.

Damage to the soil was assessed on the basis of the observations of the soil surface on a circular sample plot with a diameter of 50 cm, around each of the 36 nodal points created as a result of establishing a grid of squares in accordance with the classification developed by Dyrness (1965) and modified by Giefing (1999):

1. undisturbed soil – forest litter retained, no traces of compaction, disturbance class $R = 0$,
2. slightly damaged soil, this class consists of three subclasses:
 - a) litter removed, mineral soil exposed but not disturbed, disturbance class $R = 1$,
 - b) mineral soil mixed with forest litter, disturbance class $R = 2$,

c) litter and logging slash covered with mineral soil with a thickness of up to about 5 cm, disturbance class $R = 3$,

3. heavily damaged soil, soil surface layer removed, deeper layers exposed, soil surface sparsely covered with forest litter or logging slash, disturbance class $R = 4$,

4. compacted soil, visible traces of compaction by a logging vehicle or a load, disturbance class $R = 5$.

For the digital presentation of the results obtained, a soil disturbance indicator (Ng), based on the Ud indicator used to assess stand damage (Sosnowski, 1999), was developed for the purpose of this study, according to the following formula:

$$Ng = \frac{\sum I_{R(1-5)} \times R_{1-5}}{N} \quad (2)$$

where I_R – is the number of nodal points in class R of soil disturbance, N – is the number of all nodal points on the study site and R – is a soil disturbance class.

In accordance with the method proposed by Grodecki *et al.* (2000), the following soil damage indicators were also calculated (modified according to the adopted marking of individual damage classes and their measurement methods):

Soil damage indicator W_G :

$$W_G = \frac{\sum I_{R(1-5)}}{N} \times 100\% \quad (3)$$

Heavy soil damage indicator W_{Gd} :

$$W_{Gd} = \frac{\sum I_{R(4-5)}}{N} \times 100\% \quad (4)$$

Synthetic soil damage indicator S_{WG} :

$$S_{WG} = \frac{0,1 \times I_{R1} + 0,3 \times I_{R2} + 1 \times I_{R3} + 3 \times I_{R4} + 3 \times I_{R5}}{N} \quad (5)$$

Twice, before and after the performed harvesting operation, trees growing on the sample plots were inventoried and measured, taking into account only the trees with a DBH exceeding 7 cm. Then, the intensity of cuts in terms of quantity and volume was calculated.

To find out whether all the applied methods and indicators rank the sample plots in a similar way according to the growing level of damage to the soil, a three-digit scale was used:

- 1 – area with the lowest level of soil damage,
- 2 – area with an average level of soil damage and
- 3 – area with the highest level of soil damage.

3. Results and discussion

The three established sample plots differed in both the number and volume of the trees growing on them, as well as in the intensity of the performed cuts. Also, the average volume of removed trees differed significantly from 0.83 m³ on plot B to nearly 3 m³ on plot C (Table 2).

This situation – variable stand characteristics and intensified cuts – made it difficult to arrive at generalisations related to the description of the performed operation and extent of damage in the stand under review. However, for the implementation of the set objective, this situation was beneficial because the comparison of different methods of estimating and assessing the damage caused by harvesting operations was possible only on the plots where its intensity was high.

The percentage share of disturbed soil on the plots under review differed, as illustrated in Fig. 1.

The smallest damage was found on plot B – approximately 2.6%, more than 1.7 times larger for plot A and more than twice as large, around 5.8%, for plot C. The results obtained were similar to or greater than those observed in the previous studies in the thinned pine stands where, after skidding using farm tractors, the percentage share of the soil disturbed during harvesting operations ranged from 2.6% to 3.6%, depending on stand age (Sowa, Kulak, 2008a). Damage to the timber stands was usually higher, reaching 13% if the skidding was done by a farm tractor under the mountain conditions (Dudek, Sosnowski 2011). Other studies (Kulak, Barszcz, 2008) carried out in a fir-beech timber stand in a similar upland fresh deciduous forest habitat (Lwyżów) revealed that damage could amount to 12–18% of the area, depending on the harvesting machine used.

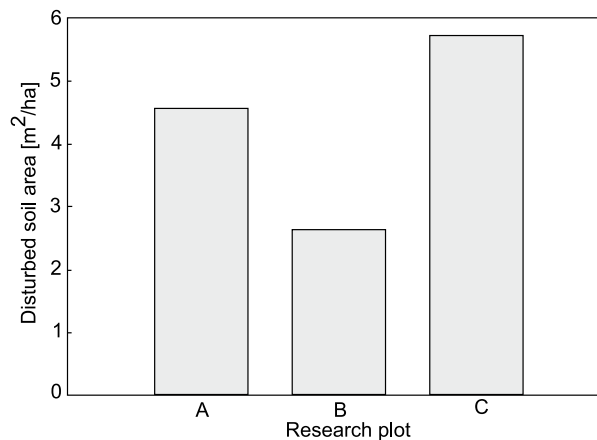
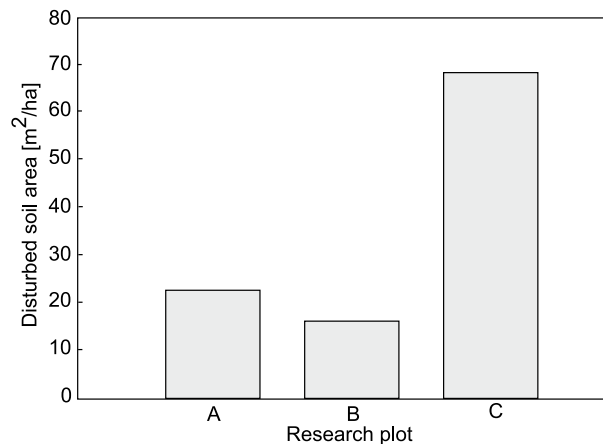
The obtained ranking of sample plots in terms of the extent of soil surface disturbance shows the relationship existing between the growing intensity of cuts and the average volume of the removed trees. Such relationships between the extent of the damage caused by harvesting and the intensity of cuts were also confirmed in the studies of large-scale damage (Pinard *et al.* 2000). It was found that with the increasing intensity of cuts, the likelihood of disturbances in the topsoil (Sowa, Kulak 2008b) also increased.

The volume of the disturbed soil differentiated the sample plots even better (over proportionally) than the surface area of the damaged soil (Fig. 2).

A conclusion can be drawn there from that the depths of the occurred soil disturbances were significantly larger on plot C than on plots A and B. The mean values

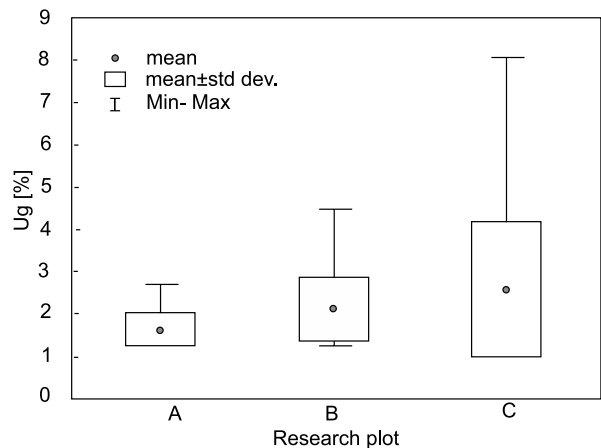
Table 2. Characteristic of research plots

Specification		Sample plot		
		A	B	C
Number of trees before cutting	trees/ha	512	868	172
Number of removed trees	trees/ha	112	212	92
Tree volume before cutting	m ³ /ha	340.4	449.6	428.9
Volume of removed trees	m ³ /ha	155.9	175.6	272.0
Percentage of removed trees	%	21.9	24.4	53.5
Percentage of removed tree volume	%	45.8	39.1	63.4
Average volume of trees being removed	m ³	1.39	0.83	2.95

**Fig. 1.** Disturbed soil surface area in tree research plots**Fig. 2.** Soil disturbance volume in tree research plots

and differences in the depth of damage to the soil on individual plots are shown in Fig. 3.

The average depth of soil disturbances increased from plot A through plot B to plot C amounting to 4.1, 6.9 and 9.3 cm, respectively. Significant differences in the maximum depth of damage to the soil were observed, ranging from 10 cm on plot A, 20 cm on plot B to 40 cm on plot C. These results can be attributed to two facts. First, the stand under review sloped in the direction from A to C, which is linked with soil moisture increasing in the same direction. This in turn was associated with the level of damage caused by harvesting. On more moist soils, the level of soil damage is higher (Sosnowski, 2003, Wood *et al.*, 2002). The significantly greater average volume of the removed trees amounting to nearly 3 m³ was another factor that might have caused a much deeper damage to the soil on plot C. According to Zastocki (2003), the greater damage caused during the extraction of larger trees arise from the fact that their weight is spread over a smaller area than in the case of smaller trees when the load of a similar weight is distributed over a larger area.

**Fig. 3.** Differences in soil disturbance depth in tree research plots

Values of *Ug* indicators characterising soil damage on individual plots were calculated according to the adopted methodology. The obtained results are shown in Fig. 4.

The values of Ug indicator rank the sample plots in the same way as do the soil disturbance volumes in Fig. 2. This is due to the fact that Ug indicator also carries information about the volume of the disturbed soil, though limited only to its 10-cm thick top layer. Therefore, the extremely deep ruts observed on plot C had no great effect on the value of this indicator.

The obtained values of the indicators do not differ from those reported in the literature. In the stands under complex (selection and shelterwood) system, Ug indicator ranged from 4.0% to 8.4%, depending on the harvesting system used and the distance between strip roads (Suwała 2003).

The classification of soil damage at nodal points performed according to Dyrness' scale allowed the specification of damage observed on individual plots (Table 3).

Plot B was characterised by the largest share of undisturbed spots points amounting to nearly 64%, on plot A it was much less – 42%, and on plot C – only 22%.

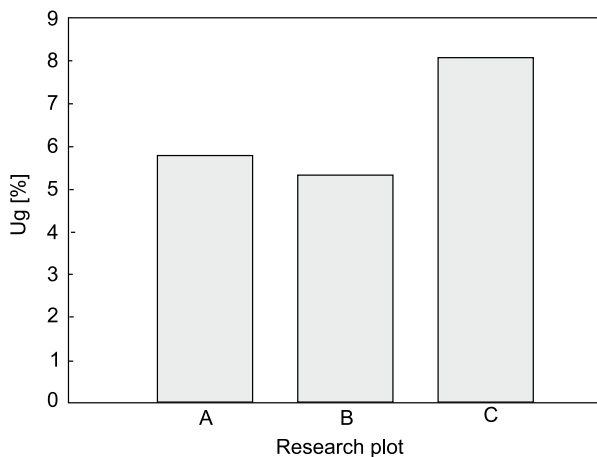


Fig. 4. Value of Ug indicator in tree research plots

A slightly damaged soil (disturbance class $R = 1, 2$ and 3) was observed to a similar extent on all the analysed plots, and the percentage share of these classes ranged from 19% to 33%. Significant differences were observed on the sample plots in the share of heavily damaged soil ($R = 4$). On plot B, this form of damage was absent, on plot A it was found only at one nodal point, while on plot C – at nearly 20% of points.

Soil disturbance indicators (Ng), soil damage indicators (W_G), heavy soil damage indicators (W_{Gd}) and a synthetic soil damage indicator (S_{WG}) outlined in Section 2 were calculated on the basis of the percentage shares of soil damage classes (Table 3). The calculation results obtained are shown in Table 4.

The quoted indicators are not comparable with each other. While indicators W_G and W_{Gd} carry simple information about the percentage share of, respectively, points with detected damage and points with damage in the two highest classes, indicators Ng and S_{WG} are associated with assigning weights to the various forms of soil damage. In comparison with the studies by Glazar and Maciejewska (2009), who determined the value of indicators W_G , W_{Gd} and S_{WG} at a maximum level of 25%, 14% and 0.42, the results obtained were even three times higher. However, research conducted by the cited authors referred to the timber stand.

For comparison, to find whether all the applied research methods rank the plots in an identical way by the increasing level of soil damage, sample plots with the assigned digits 1–3 are shown in Table 5. According to the adopted method, 1 indicates the smallest, while 3 indicates the largest damage.

In addition to the depth of soil disturbances, all the characteristics and indicators of soil damage ranked the sample plots in the same way in terms of the extent of damage. The applied measures and classifications of soil disturbances are descriptive – all indicators are

Table 3. Soil disturbance in tree research plots

Soil – name and disturbance class R	A		B		C	
	number of points	[%]	number of points	[%]	number of points	[%]
Undisturbed ($R = 0$)	15	41.7	23	63.9	8	22.2
Slightly damaged ($R = 1, 2, 3$)	11	30.6	7	19.4	12	33.3
Severely damaged ($R = 4$)	1	2.8	0	0.0	7	19.4
Compacted ($R = 5$)	9	25.0	6	16.7	9	25

Table 4. Values of soil damage indicators on study areas

Indicator, symbol	A	B	C
Soil disturbance indicator, Ng	1.72	1.08	2.63
Soil damage indicator, W_G [%]	58.3	36.1	77.8
Severe soil damage indicator, w_{gd} [%]	27.8	16.7	44.4
Synthetic indicator of soil damage, S_{WG}	0.88	0.53	1.43

Table 5. Classification of study areas according to the extent of soil damage relative to the applied soil damage assessment method

Indicator symbol	A	B	C
Disturbed soil surface area	2	1	3
Disturbed soil volume	2	1	3
Disturbed soil depth	1	2	3
Ug [%]	2	1	3
Ng	2	1	3
W_G [%]	2	1	3
W_{Gd} [%]	2	1	3
S_{WG}	2	1	3

Description as in Table 4.

1 – area with the lowest level of damage, 2 – area with an average level of damage, 3 – area with the highest level of damage

based on Dyrness' classification, and areal – the information pertains to the surface area of the disturbed soil. The third characteristic, i.e. the depth of the detected damage is described, in addition to direct measurements, by the volume of soil damage and the value of the Ug indicator. Nevertheless, the depth of the furrows and ruts has a limited effect on the value of this indicator, because the ruts deeper than 10 cm do not change its value. With minor differences in the surface area of the disturbed soil in the compared stands and, at the same time, with large differences in the depth of damage to the soil, surface area measurements may rank the compared cutting areas in a different way than volume measurements. It seems, therefore, appropriate, while using only qualitative indicators for the assessment of damage, to supplement additional information about the depth of the damage.

4. Conclusions

In the analysed stand, damage caused during harvesting operations covered 2.6–5.8% of the area, which should be considered an average value, close to that reported in the literature. Also other calculated characteristics of soil disturbances (volume) and indicators (Ug , W_G , W_{Gd} , S_{WG}) did not differ from literature data.

The presented results show that most of the used disturbance measures of assessing soil surface disturbances were comparable, ranking the study sites in the same way by the increasing the extent of damage. All of the methods may, therefore, be used for simple comparisons of the extent of damage. Indicators Ng , W_G , W_{Gd} and S_{WG} are worth recommending in the first place due to the ease of field research. However, with the exclusive use of these indicators, it would be desirable to provide additional information about the depths of the ruts created during harvesting operations.

A more complete picture regarding the extent and nature of the observed soil damage can be obtained taking into account the depth of the damage by calculating the volume of the damage or the value of the Ug indicator.

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