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Soil Characteristics in Oak Lowland Stand – A Case Study of a 6-Wheeled Forwarder's Impact on Forest Soil

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Abstract

*The behavior of the vehicle-soil interaction and reduction of the possible soil damage to an acceptable level is one of the goals of forest engineering. This study aimed to analyze the impact of a 6-wheeled forwarder on water-physical soil characteristics on lowland soil – pseudogley. The research was conducted using a 17-ton Timberjack 1710B forwarder, which forwarded 694.1 m^3 volume of oak (*Quercus robur *L.) assortments. Soil characteristics were measured after each of the eight passes of the loaded forwarder. Bulk density measured on the surface layer ranged from 1.01–1.23 (*Me=1.10*) g/cm^3 (undisturbed soil); 1.14–1.70 g/cm^3 (multiple passes of the loaded forwarder). The highest soil density increase was observed after the first pass of the loaded forwarder (16%). Soil solid phase ranged from 2.49 to 2.73 g/cm^3 with no statistically significant difference between undisturbed soil and soil after multiple passes of the vehicle. The highest porosity decrease was observed after the first pass of the loaded forwarder (10%). The highest soil water retention capacity decrease was observed after the first pass of the loaded forwarder (3%). The highest soil air capacity decrease was observed after the first pass of the loaded forwarder (30%) compared to the undisturbed soil of the forest stand.*

Keywords: pseudogley (planosol), forwarding timber, vehicle-soil impact

1. Introduction

Ground-based timber harvesting systems are still dominant in global timber supply chains. Due to high machine and payload weight, impact on the forest soil is unavoidable. Sustainable harvesting operations have never been under higher pressuer, balancing between favourable operational conditions, environmental consequences, climatic extremes and timber supply chain deadlines, requiring a constant and solid revenue. Soil disturbance is often an unavoidable consequence of intensive harvesting operations and causes undesirable effects on soil and vegetation (Cambi et al. 2015a, Cambi et al. 2015b, Cambi et al. 2016, Solgi et al. 2021, Ganatsios et al. 2021). Soil compaction negatively impacts soil respiration, microbiological activity and, finally, forest growth. Rutting causes compaction of the bottom of the ruts, while retained water on the soil surface can completely prevent the activity of roots and aerobic microorganisms. Soil compaction decreases the number of capillary pores and hence water permeability, which also means that water conductivity can be obstructed (Halvorson et al. 2003). In order to achieve the least possible negative impact on the forest ecosystem, good planning actions and adequate machinery are necessary.

Multiple passes of the forwarder along the same trail lead to excessive soil disturbance, compaction and changes in the water-physical soil characteristics (Uusitalo et al. 2020, Lee et al. 2020, Starke et al. 2020, Zemánek and Neruda 2021, Schönauer et al. 2021, Marra et al. 2022).

The main water-physical soil characteristics can be seen in bulk density and porosity changes. The proportion of mineral versus organic particles, to a large extent, determines bulk density. On the other hand, porosity is the volume of soil filled with either water or air. It is inversely related to bulk density; as bulk density increases, porosity decreases. Soil texture is an essential determinant of porosity. The macropores of sands promote air and water movement, but limit their water-holding capacity. Because of their micropores, clays have excellent water holding capacity, but poor air and water movement and, hence, poor drainage. Because of their low bulk density, organic soils tend to have much higher porosity than mineral soils (Mobilian and Craft 2022).

Soil deformation is a consequence of the machine traffic, when pores can no longer be compressed. Onwards soil deformation occurs when shear strength is exceeded. Soil bearing capacity is defined as the maximum permissible tire pressure of the vehicle without damaging the soil (Saarilahti 2002), depending on the type and texture of the soil, humus layer and skeletal particles (permanent parameters of soil), and the only variable parameter – soil moisture (Vega-Nieva et al. 2009, Poršinsky et al. 2011). Very wet clay and loamy soils are typical for extreme soil deformations (Ampoorter et al. 2010). Rut depths of 10 cm are generally considered the breakeven point for the acceptable level of ruts (Uusitalo et al. 2019). Nugent et al. (2003) conducted a study to characterize the effects of wood harvesting and extraction machinery traffic on sensitive forest sites with peat soils. The influence of harvesting and extraction is confined to the top 40 cm layer of a soil profile. The damage may be reduced by controlling the number of machine passes and limiting the contact pressure imposed by wheels or tracks by adequately selecting the size and type of traction mechanism (tires or tracks). This was confirmed in later studies (Uusitalo and Ala-Ilomäki 2013, Allman et al. 2017, Toivio et al. 2017).

Timber transport in the lowland forests of Croatia is based on forwarding timber cut mainly by chain saws and processed to assortments by the stump, similar to other European countries where forwarders are used in partly mechanized systems that integrate motor-manual felling and processing of trees (Borz et al. 2021, Mederski et al. 2021). Lowland clay soils have limited bearing capacity due to their periodically increased moisture during the year. Pseudogley soils of solid and plastic consistency (low moisture percentage) are suitable for vehicle mobility (Poršinsky et al. 2006). However, when the moisture is higher, pseudogley soil becomes mostly unsuitable for vehicle trafficking.

Understanding the behavior of the vehicle-soil interaction and restricting the possible soil damage to an acceptable level is one of the tasks of forest engineering (Poršinsky et al. 2006). This study aims to analyze the impact of a 6-wheeled forwarder on water-physical soil characteristics on lowland pseudogley soil.

2. Materials and Methods

2.1 Study Site

The fieldwork for this study was done in a central lowland part of Croatia in the management unit (MU) Josip Kozarac, sub compartments 14a and 14b (N 45°20'–45°26'; E 16°45'–16°53'; 95 m a.s.l.) located approximately 100 km from Zagreb, the capital city of Croatia. The test study site was within a 140-year-old stand of pedunculate oak and dyer's broom (*Genisto elatae-Quercetum roboris caricetosum remote* Horvat 1938) on a pseudogley soil type. Growing stock in the sub compartments was 2968 m^3 or 195.5 m^3/ha (39 trees/ha). After felling and processing, logs amounted to 115.9 m^3/ha, and long firewood to 43.9 m^3/ha. The average distance between cut trees was 16.1 m, and the average tree of the compartment was 5.07 m^3 in volume.

2.2 Defining Soil Characteristics

The soil type of the study test site is a pseudogley (planosol) with a high share of clay particles and an impermeable layer for water draining at 30–40 cm depth. Porosity grades range from 42% to 56%, water retention capacity is approximately at 40% and soil air capacity is very low, below 10% (Martinović 2003, Pernar 2007). Soil texture is 28.8% sand, 40.3% silt and 30.9% clay (Fig. 1).

Penetration resistance of undisturbed soil of the study site was measured by a hand cone penetrometer (Eijkelkamp PenetroLogger), with a 2 cm^2 base area and 30° cone angle. Measurements were taken up to 80 cm at a speed of 2 cm/s. A standardized value of the cone penetration measurement (ASAE EP 542 1999) was used at 15 cm depth, i.e. the cone index (*CI*). Soil shear strength of undisturbed soil of the study site was determined with a vane tester (Eijkelkamp), 32×16 mm wing dimensions, a measuring range of 0 to 260 kPa, and reading accuracy of 4 kPa, on the surface layer of forest soil, at 15 and 30 cm in depth. Cone index of undisturbed soil at the study site CI_{0-15} was 0.744 MPa; CI_{15-30}=0.859 MPa (Fig. 2A). Average soil shear strength of the study site (Fig. 2B) was 41±15 kPa (median 36 kPa).

Water retention prevents the activity of roots and aerobic microorganisms and reduces soil shear strength. Also, pseudogley soils in increased moisture conditions are more susceptible to deformation (Fig. 1.). Soil moisture was measured with a ThetaProbe hygrometer. Rain occurred at the study site a few days before and continued during the measurements. This led to specific soil moisture conditions. The current moisture of the surface soil layer ranged from 30.7 to 63.9 vol.%, influenced by the micro conditions of the location. The average current moisture of

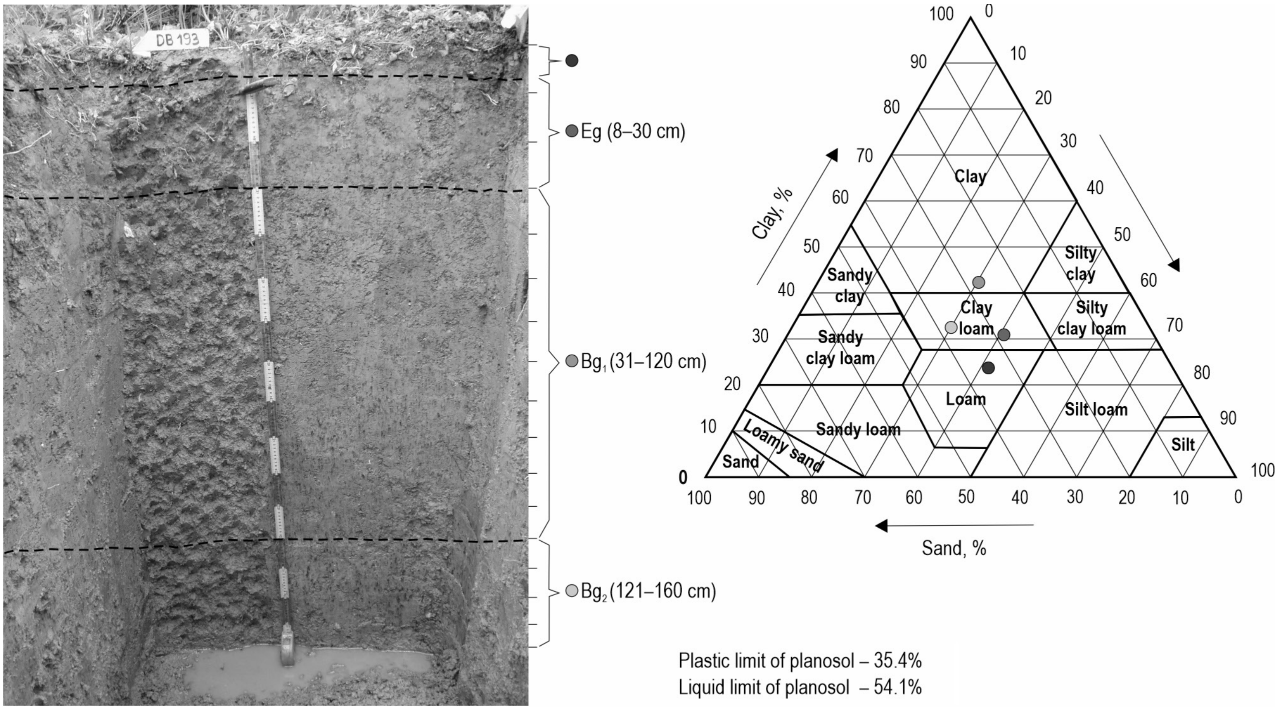


Fig. 1 Pedological soil profile and texture soil classification of study site

the accumulative humus layer was 43.3±5.9 vol.% (a value slightly below the water soil retention capacity). With an increase in the soil depth, current moisture was in decrease. This indicated saturation of the soil surface layer with water, which led to reduced soil bearing capacity.

Measurements of soil water-physical characteristics were done with a Kopeckey cylinder (100 cm^3). Five samples were taken at soil depth of 15 cm and transported to the laboratory, where bulk density, soil porosity, soil water retention capacity and soil capacity for air were determined for each soil sample. The

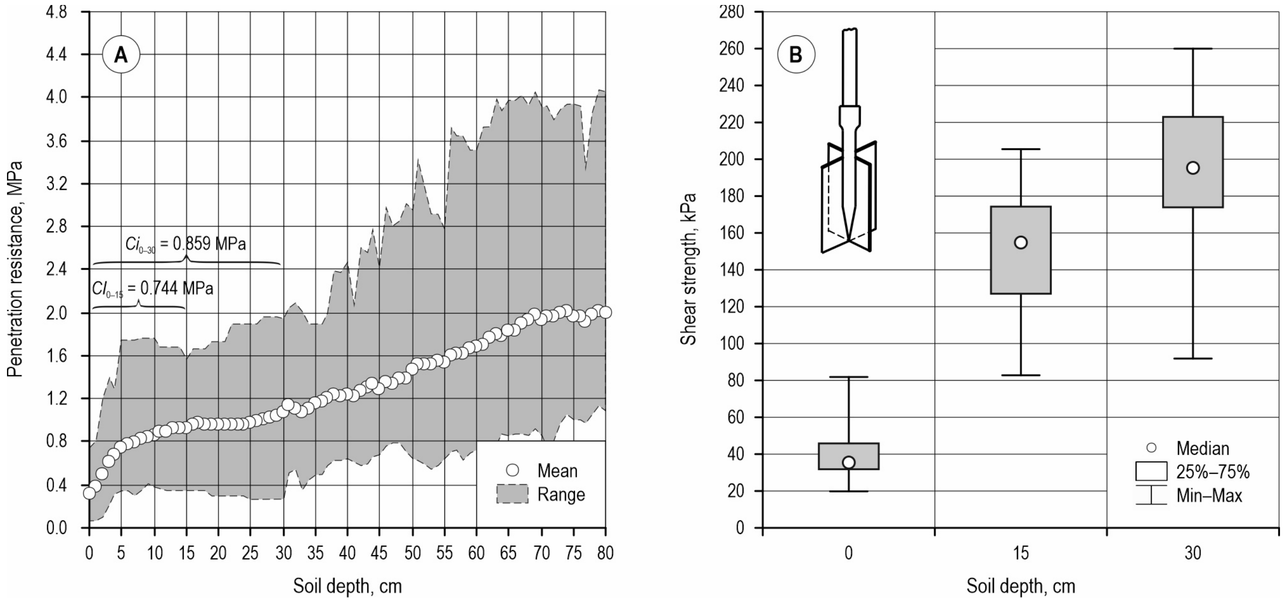
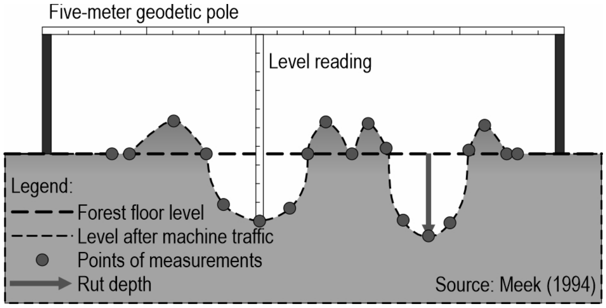


Fig. 2 A) Penetration resistance and B) Soil shear strength of study site



Source: Meek (1994)

Fig. 3 Technique used for rut depth measurements

samples were collected before machine traffic, and after each of the eight passes of the loaded forwarder. Standard laboratory analyses with a pycnometer were made.

2.3 Vehicle and Load Characteristics

The research was conducted using a 17-ton Timberjack 1710 forwarder, length 10.45 m, width 3.01 m, height 3.90 m, driven by a six-cylinder water-cooled Perkins diesel engine 1306-8TI with pre-charging, of the nominal power of 156.5 kW at 2400 min^{-1} and 847 Nm of the maximum torque at 1600 min^{-1}. The forwarder was equipped with a hydraulic crane TJ 111 F 72, with a boom lifting torque of 151 kNm at the maximum range of 7.2 m. Forwarder front tires were Nokian Tractor special 700/70-34 16 PR and rear tires were Nokian ELS L2 650/65-26.5 20 PR.

The estimation of allowed bearing capacities (contact ground pressure) was based on the Nominal Ground Pressure (*NGP*, kPa) calculation by Mellgren (1980). Rutting was measured according to Meek (1994) and Nugent et al. (2003) with a geodetic pole 5 m in length after every vehicle pass (Fig. 3). In practice, Saarilahti (2002) recommends the acceptable average rut depth up to 10 cm on 10% of the total length of disturbed soil of a cut-block.

The load consisted of oak (*Quercus robur* L.) assortments, i.e. logs and long firewood (Fig. 4) of 13.6 m^3 volume each with the average log volume of 0.547±0.510 m^3. In total, 694.1 m^3 of oak logs were forwarded from the stump to the roadside landing in 51 cycles. The average dimensions of logs were 41 cm mid-diameter and 3.6 m in length.

All data were checked for normality (Kolmogorov–Smirnov test), and homogeneity of variance (Levene test) and then analysis of soil properties was made with ANOVA using Statistica 7 software.

Fig. 4 Loading oak roundwood by a Timberjack 1710B

3. Results

Bulk density measured on the surface layer ranged from 1.01–1.23 (*Me*=1.10) g/cm^3 (undisturbed soil); 1.14–1.70 g/cm^3 (multiple passes of the loaded forwarder). ANOVA showed a statistically significant difference between forwarder passes and undisturbed soil ($p<0.0001$; $MS=0.09$; $df=9$). The highest soil density increase was observed after the first pass of the loaded forwarder (16%); after the first pass of the loaded forwarder, *Me*=1.31 g/cm^3, and after three passes, *Me*=1.35 g/cm^3 (Fig. 5A).

Soil solid phase ranged from 2.49 to 2.73 g/cm^3. Analysis of ANOVA did not show a statistically significant difference between undisturbed soil and soil after multiple passes of loaded forwarder ($p=0.4819$; $MS=0.00$, $df=9$).

Along with the increase of the soil density, soil porosity decreased. The highest porosity decrease was observed after the first pass of the loaded forwarder (10%). Porosity decreased from 61.2 vol.% to 46 vol.% after the eighth pass of the loaded forwarder. ANOVA showed a statistically significant difference between forwarder passes ($p<0.0001$; $MS=130.79$; $df=9$).

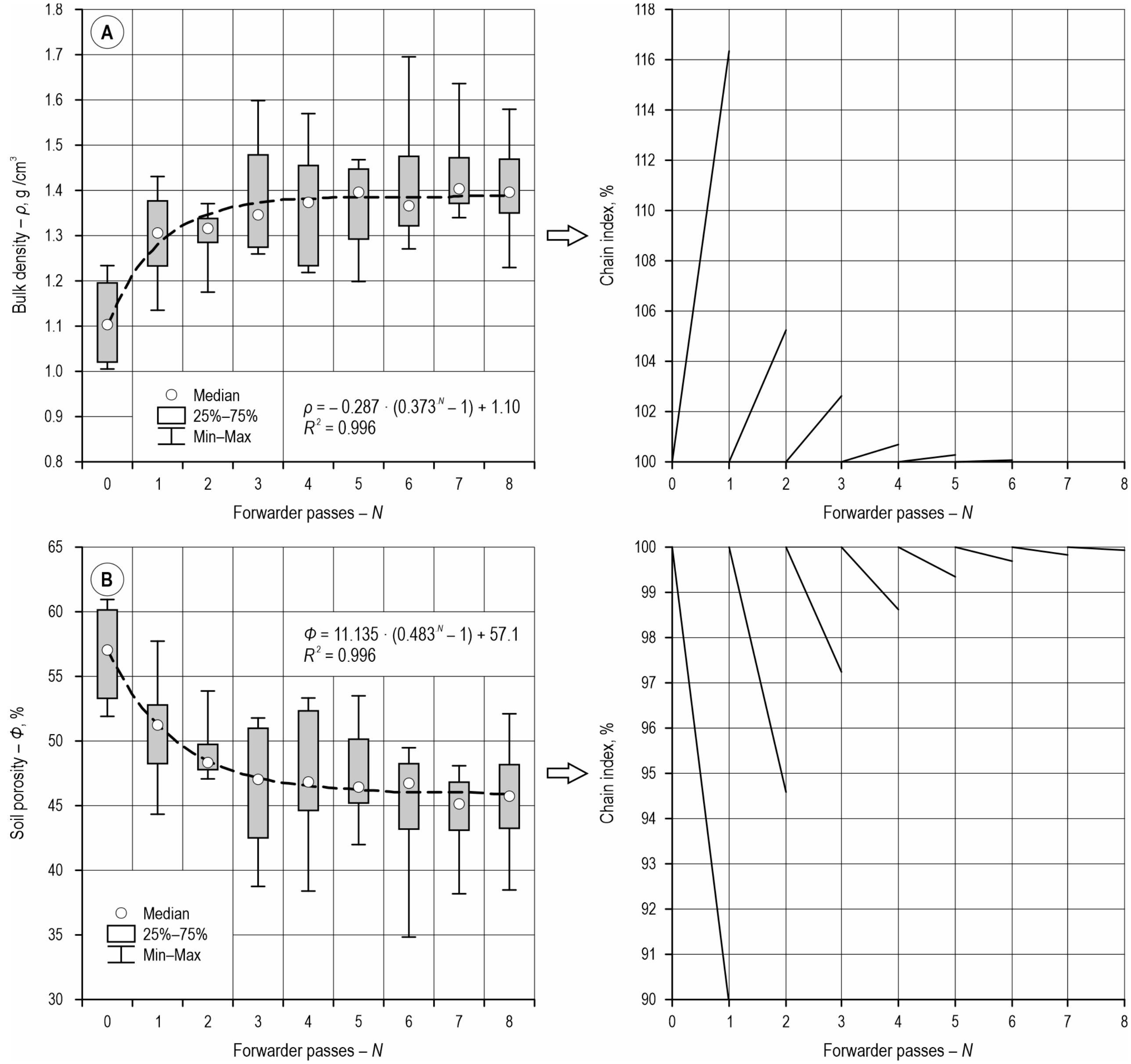


Fig. 5 Median, 25%–75% confidence level, minimum-maximum and chain index for A) bulk density and B) soil porosity

The regression line and chain index suggest that the highest soil porosity decrease occurs after the third pass of the loaded forwarder (Fig. 5B).

The maximum soil water retention capacity is reached when all soil pores (micro and macro) contain water. Then air capacity of the soil is equal to zero; for pseudogley soil, the maximum soil water retention capacity occurs in the winter-spring when the impermeable layer retains water in the upper layers of the soil. However, the measurements on the study site took place after the dry period; a few days before the measurements, the rain started, which led to specific soil conditions.

The highest soil water retention capacity decrease was observed after the first pass of the loaded forwarder (3%). The median soil water retention capacity for undisturbed soil was 45.96 vol.% and 41.79 vol.% after the third pass of the loaded forwarder. ANOVA did not show a statistically significant difference between undisturbed soil and soil after multiple passes of the loaded forwarder (p=0.0737; MS=51.16, df=9) (Fig. 6A).

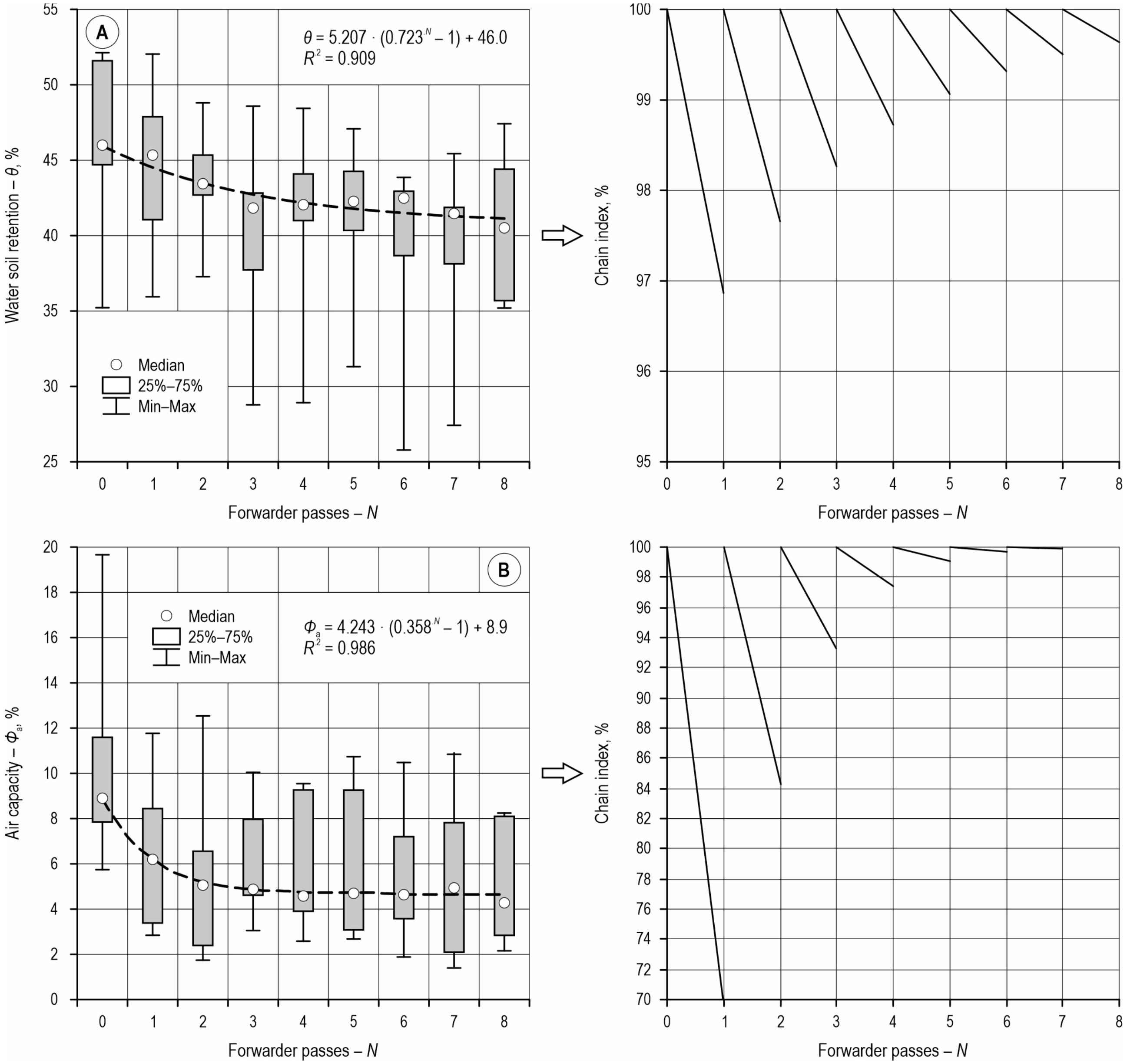


Fig. 6 Median, 25%–75% confidence level and minimum-maximum, followed by a chain index for A) soil water retention and B) soil air porosity

The highest soil air capacity decrease was observed after the first pass of the loaded forwarder (30%) compared to the undisturbed soil of the forest stand. Soil air capacity decreased from an initial 8.92 vol.% to 4.35 vol% after eight passes of the loaded forwarder. ANOVA showed statistically significant difference between passes (p=0.0256; MS=23.98; df=9). The regression line and chain index suggest that the highest decrease of soil air capacity occurs after the first three passes of the loaded forwarder (Fig. 6B).

The rutting results should be analyzed through the interaction of soil characteristics, soil water dynamics and soil bearing capacity after unloaded and loaded forwarder passes on trails of the study site. When analyzing rut depth (Fig. 7A), it is evident that ruts deeper than 10 cm, as proposed by Saarilahti (2002), were observed almost from the beginning, i.e. the second pass of the loaded forwarder with Me=17.79 cm and continued to increase up to the last, eighth pass with Me=35.09 cm and the utterly unacceptable maximum of z=64.50 cm (Fig. 7B).

A single pass of the forwarder on the same track comprised of three wheels with summarized load weight 89.9 kN (50.2+19.8+19.8), but also with three wheels of the loaded forwarder 167.2 kN (62.6+52.3+52.3) with a load of 13.6 m^3. *NGP* of the unloaded forwarder was 158 kPa (78+40+40) and *NGP* of the loaded forwarder was 309 kPa (97+106+106). The *CI/NGP* ratio (Wronski and Humphreys 1994) of the study site was 2.2.

Figure 7B clearly shows unacceptable rut depth on the forwarder trail. During timber transport, vehicles must remain all the time on the secondary traffic infrastructure network, in this case trail network, to avoid further disturbance of the stand. Still, compaction and rutting as in Figure 7B will lead to wheel slip, which decreases vehicles productivity, while increasing energy loss and fuel consumption.

4. Discussion

In lowland even-aged forests of Croatia, felling is mostly done motor-manually by chain-saws, and timber assortments are transported from the stump to the roadside landing by six- or eight-wheeled forwarders. Vehicle movement and multiple passes induce pressure on the soil surface. The bearing capacity of the soil decreases if elasticity is disturbed, and in the case of pseudogley soils, as in this research, soil moisture is the main limiting factor of the soil bearing capacity (Poršinsky et al. 2011) and consequently of operational planning. Reduced soil-bearing capacity causes restricted mobility and decreases the forwarder's productivity, increasing the damage caused to forest soil reflected in its compaction and rutting. The wetter the soil, the more susceptible the soil is to disturbance and plastic deformations.

Marra et al. (2022) found that, after ten passes of a tractor with a trailer (at slope of 25% and transported timber volume of 127 m^3), a significant increase in the soil bulk density values (40%) occurred. The impact

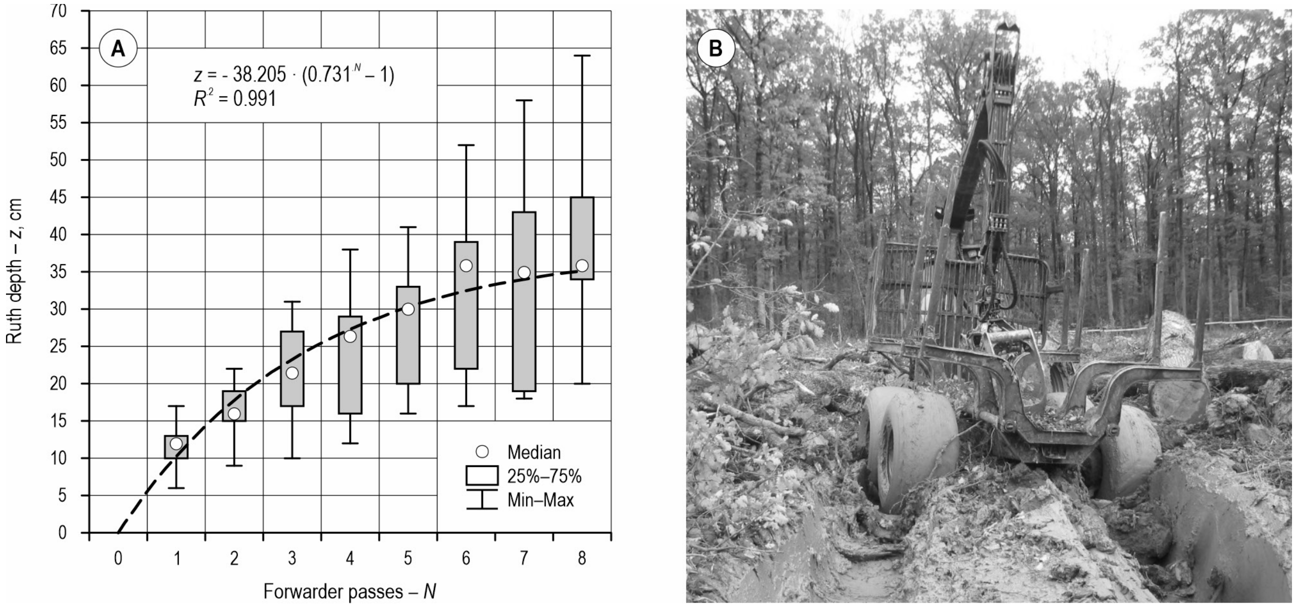


Fig. 7 Rutting A) median, 25%–75% confidence level and minimum-maximum each pass and B) unacceptable rut depth at study site

on the soil was similar to the increase of the bulk density values of our research, ~27%. Schönauer et al. (2022) argue that the first machine pass prevailingly leads to soil compaction, and additional machine passes result in a lower increase in the soil bulk density since preceding passes pre-compacted the soil already. Authors measured ruts with an average of 6.3±2.1 cm, and a maximum depth of 11.6 cm, which can be explained with lower initial soil moisture content of 29 vol.%. Starke et al. (2020) used a new 10-wheel triple-bogie forwarder to promote sustainable forest management by reducing the ecological impact of forest operations, especially under soft-soil working conditions after forwarding 90 m^3 of timber. Rut depth of 10 cm (5.8–7.2 cm) was not exceeded; average soil shear strength was 67 kPa and volumetric water content was 43%. Observed forwarder configurations ranked in the lowest-impact machine categories on related soil stability classes. In our research, the average current moisture of the accumulative humus layer was 43.3±5.9 vol.%. Ala-Ilomäki et al. (2021) investigated the effect of an eight- and ten-wheeled forwarder equipped with five different bogie track sets in a peatland and concluded that using tracks is essential on soils with a lower bearing capacity, especially Fomatec tracks (EFwo). Zemánek and Neruda (2021) showed that the rut depth after ten forwarder passes could be decreased by 50% when using the tracked type of the forwarder chassis. Labelle and Jaeger (2011) stated that, during regularly scheduled harvesting operations using CTL systems, dry soil bulk density increased by 19% in machine tracks. The authors also noticed that soil compaction occurred at the moment of the machine traffic and that bulk density increased 26 months after timber forwarding. As a possible explanation for this phenomenon, the authors indicated that the increased solar radiation and temperature on trails are a consequence of a clear-cut. This possibly increased the rate of biological activity and the decomposition of organic matter from the sheared-off or dead roots. The decreased organic matter content could explain the increasing soil density long after the machine traffic. Chain indexes showed the highest increase after the first forwarder pass, similar to Kormanek and Dvořák (2022), where a single small harvester (5.3 t) pass affected soil parameters; its eight wheels passed one after the other, causing multiple pressures. Ring et al (2021) suggest that there is considerable scope for reducing rutting during off-road forest transportation by acknowledging the variability of ground conditions and continuing to develop planning tools and onsite procedures such as ground protection.

In the Croatian lowland, forwarders are mostly equipped with tires characterized by deeper and sparser tread patterns, a so-called aggressive tread (Poršinsky et al. 2012). Such a tread pattern reduces wheel slippage but increases damage to soil and tree roots (Sutherland 2003). The use of tires with shallower and denser tread patterns (so-called nonaggressive tread), which reduces soil damage but increases wheel slippage, and is more suitable for use than tracks on the wheels of the rear (bogie) axle of forwarders, is more an exception than a rule (Poršinsky 2005). The same applies to improving soil-bearing capacity conditions on trails by forming a cover of branches or 3–4 m long firewood (Poršinsky et al. 2012).

Time of operations is also one of the essential planning activities. Frozen subsoils are ideal for forest exploitation activities since soil damage through compaction and deformation is minimized (De Schrijver et al. 2018). Hoffmann et al. (2022) state that depth-to-water (DTW) maps are desirable in forest management for decreasing traffic-induced soil impacts by identifying sensitive areas that should be avoided during harvesting operations. DTW maps are supportive during the planning phase and during the execution of operations. Still, the creation of practicable DTW maps relies on the availability of high-resolution digital terrain models (DTMs), which vary from country to country. Measuring penetration resistance, soil shear strength and current soil moisture is a simple way of establishing stand conditions but is highly dependent on climatic elements. Connecting forest soil parameters to long-term monitoring of climatic elements is also one of the future needs in forestry planning (Đuka et al. 2018).

5. Conclusions

The present study broadens our knowledge about the impact of heavy forest machinery on soil conditions. It has shown that the first three passes of a loaded forwarder are crucial for the compaction of the soil, bulk density, soil porosity and water and air capacity. For pseudogley soil, the maximum soil water retention capacity occurs in winter-spring when the impermeable layer retains water in the upper layers of the soil. The measurements on the study site were planned to take place after a dry period; however, rain started a few days before the measurements. That created specific soil conditions and led to specific results: high moisture content, slippage of wheels, high soil compaction, a decrease of high porosity, and a decrease of 30% of the highest soil air capacity after the first pass of the loaded forwarder. These results showed that for minimizing the impact on forest soil during timber forwarding, good timing and planning of forest operations are vital, but as the other research showed, the use of tracks and eight- to ten-wheeled forwarders can also reduce negative environmental consequences, and lead to sustainability.

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Conflicts of Interest: The authors declare no conflict of interest.

6. References

Ala-Ilomäki, J., Lindeman, H., Mola-Yudego, B., Prinz, R., Väätäinend, K., Talbot, B., Routa, J., 2021: The effect of bogie track and forwarder design on rut formation in a peatland. Int. J. For. Eng. 32(1): 12–19. https://doi.org/10.1080/14942119.2021.1935167

Allman, M., Jankovský, M., Messingerová, V., Allmanová, Z., 2017: Soil moisture content as a predictor of soil disturbance caused by wheeled forest harvesting machines on soils of the Western Carpathians. J. For. Res. 28: 283–289. https://doi.org/10.1007/s11676-016-0326-y

Ampoorter, E., Van Nevel, L., De Vos, B., Hermy, M., Verheyen, K., 2010: Assessing the effects of initial soil characteristics, machine mass and traffic intensity on forest soil compaction. For. Ecol. Manag. 260(10): 1664–1676. https://doi.org/10.1016/j.foreco.2010.08.002

ASAE EP 542, 1999: Procedures for using and reporting data obtained with the soil cone penetrometer. ASAE Standards 1999: 986–989.

Borz, S.A., Marcu, M.V., Cataldo, M.F., 2021: Evaluation of an HSM 208F 14 tone HVT-R2 Forwarder Prototype under Conditions of Steep-Terrain Low-Access Forests. Croat. j. for. eng. 42(2): 185–200. https://doi.org/10.5552/crojfe.2021.775

Cambi, M., Certini, G., Fabiano, F., Foderi, C., Laschi, A., Picchio, R., 2015a: Impact of wheeled and tracked tractors on soil physical properties in a mixed conifer stand. iForest-Biogeosci. For. 9(1): 89–94. https://doi.org/10.3832/ifor1382-008

Cambi, M., Certini, G., Neri, F., Marchi, E., 2015b: The impact of heavy traffic on forest soils: a review. For. Ecol. Manag. 338: 124–138. https://doi.org/10.1016/j.foreco.2014.11.022

Cambi, M., Grigolato, S., Neri, F., Picchio, R., Marchi, E., 2016: Effects of Forwarder Operation on Soil Physical Characteristics: a Case Study in the Italian Alps. Croat. J. For. Eng. 37(2): 233–239.

De Schrijver, A., Ampoorter, E., van der Burg, R., Demey, A., Schelfhout, S., Olsthoorn, A., De Smet, P., Vangansbeke, P., Van Nevel, L., Hommel, P., De Frenne, P., Mertens, J., Verheyen, K., Groeiplaatsverbetering, 2018: In: Kremers, S., & Boosten, M. Soil compaction and deformation in forest exploitation. Stichting Probos, Wageningen, 2018, 1–53.

Đuka, A., Poršinsky, T., Pentek, T., Pandur, Z., Janeš, D., Papa, I., 2018: Soil Measurements in the Context of Planning Harvesting Operations and Variable Climatic Conditions. South-east Eur. For. 9(1): 61–71. https://doi.org/10.15177/seefor.18-04

Ganatsios, H.P., Tsioras, P.A., Papaioannou, A.G., Blinn, C.R., 2021: Short Term Impacts of Harvesting 0perations on Soil Chemical Properties in a Mediterranean Oak Ecosystem. Croat. J. For. Eng. 42(3): 463–476. https://doi.org/10.5552/crojfe.2021.1100

Halvorson, J.J., Gatto, L.W., McCool, D.K., 2003: Overwinter changes to near-surface bulk density, penetration resistance and in-filtration rates in compacted soil. J. Terramech. 40(1): 1–24. https://doi.org/10.1016/S0022-4898(03)00014-4

Hoffmann, S., Schönauer, M., Heppelmann, J., Asikainen, A., Cacot, E., Eberhard, B., Hasenauer, H., Ivanovs, J., Jaeger, D., Lazdins, A., Mohtashami, S., Moskalik, T., Nordfjell, T., Stereńczak, K., Talbot, B., Uusitalo, J., Vuillermoz, M., Astrup, R, 2022: Trafficability Prediction Using Depth-to-Water Maps: the Status of Application in Northern and Central European Forestry. Curr. For. Rep. 8(1): 55–71. https:/doi.org/10.1007/s40725-021-00153-8

Kormanek, M., Dvořák, J., 2022: Use of impact penetrometer to determine changes in soil compactness after Entracon Sioux EH30 timber harvesting. Croat. j. for. eng. 43(2): 325–337. https://doi.org/10.5552/crojfe.2022.1054

Labelle, E.R., Jaeger, D., 2011: Soil Compaction Caused by Cut-to-Length Forest Operations and Possible Short-Term Natural Rehabilitation of Soil Density. Soil Sci. Soc. Am. J. 75(6): 2314–2329. https://doi.org/10.2136/sssaj2011.0109

Lee, E., Li, Q., Eu, S., Han, S-K., Im, S., 2020: Assessing the impacts of log extraction by typical small shovel logging system on soil physical and hydrological properties in the Republic of Korea. Heliyon 6(3): e03544. https://doi.org/10.1016/j.heliyon.2020.e03544

Marra, E., Laschi, A., Fabiano, F., Foderi, C., Neri, F., Mastrolonardo, G., Nordfjell, T., Marchi, E., 2022: Impacts of wood extraction on soil: assessing rutting and soil compaction caused by skidding and forwarding by means of traditional and innovative methods. Eur. J. For. Res. 141: 71–86. https://doi.org/10.1007/s10342-021-01420-w

Martinović, J., 2003: Management of forest soils in Croatia. Croatian Forest Research Institute, Croatian Forests, 1–525 p.

Mederski, P.S., Borz, S.A., Đuka, A., Lazdiņš, A., 2021: Challenges in Forestry and Forest Engineering – Case Studies from Four Countries in East Europe. Croat. j. for. eng. 42(1): 117–134. https://doi.org/10.5552/crojfe.2021.838

Meek, P., 1994: Effects of skidder traffic on two soils in the Canadian boreal forest, Interactive seminar and workshop »Soil, tree, machines interaction«, Feldafing, Germany, 1–8 p.

Mellgren, P.G., 1980: Terrain Classification for Canadian Forestry, FERIC, Canadian Pulp and Paper Association: Montreal, QC, Canada, 1–13 p.

Mobilian, C., Craft, C.B., 2022: Wetland Soils: Physical and Chemical Properties and Biogeochemical Processes. In Encyclopedia of Inland Waters, 2nd ed., Mehner, T., Tockner, K., Eds., Elsevier, 157–168. https://doi.org/10.1016/B978-0-12-819166-8.00049-9

Nugent, C., Kanali, C., Owende, P.M.O., Nieuwenhuis, M., Ward, S., 2003: Characteristic site disturbance due to harvesting and extraction machinery traffic on sensitive forest sites with peat soils. For. Ecol. Manag. 180(1–3): 85–98. https://doi.org/10.1016/S0378-1127(02)00628-X

Pernar, N., 2007: Tlo – nastanak, značajke, gospodarenje. Šumarski fakultet Sveučilišta u Zagrebu, 1–799 p.

Poršinsky, T., Pentek, T., Bosner, A., Stankić, I., 2012: Ecoefficient Timber Forwarding on Lowland Soft Soils. In Global Perspectives on Sustainable Forest Management, Okia, C.A., Ed., Intech Open, 275–288.

Poršinsky, T., Sraka, M., Stankić, I., 2006: Comparison of two approaches to soil strength classifications. Croat. j. for. eng. 27(1): 17–26.

Poršinsky, T., Stankić, I., Bosner, A., 2011: Ecoefficient Timber Forwarding Based on Nominal Ground Pressure Analysis. Croat. J. For. Eng. 32(1): 345–356.

Poršinsky, T., 2005: Efficiency and environmental evaluation of Timberjack 1710 forwarder on roundwood extraction from Croatian lowland forests. PhD thesis, University of Zagreb, Faculty of Forestry, Zagreb, Croatia, 1–170 p.

Ring, E., Andersson, M., Hansson, L., Jansson, G., Högbom, L., 2021: Logging Mats and Logging Residue as Ground Protection during Forwarder Traffic along Till Hillslopes. Croat. j. for. eng. 42(3): 445–462. https:/doi.org/10.5552/crojfe.2021.875

Saarilahti, M., 2002: Modelling of the wheel and soil. Forest soil properties – Survey on forest soil properties and soil compaction for studying the mobility of forest tractors (Appendix report no 8) In Soil Interaction Model – Development of a Protocol for Eco-Efficient Wood Harvesting on Sensitive Sites (Ecowood), Contract No. QLK5-1999-00991, University of Helsinki: Helsinki, Finland, 2002, 1–37 p.

Schönauer, M., Hoffmann, S., Maack, J., Jansen, M., Jaeger, D., 2021: Comparison of Selected Terramechanical Test Procedures and Cartographic Indices to Predict Rutting Caused by Machine Traffic during a Cut-to-Length Thinning Operation. Forests 12(2): 113. https://doi.org/10.3390/f12020113

Solgi, A., Naghdi, R., Zenner, E.K., Farshad, K.B., Vatani, L., 2021: Effectiveness of Erosion Control Structures in Reducing Soil Loss on Skid Trails. Croat. J. For. Eng. 42(3): 501–514. https://doi.org/10.5552/crojfe.2021.742

Starke, M., Derron, C., Heubaum, F., Ziesak, M., 2020: Rut Depth Evaluation of a Triple-Bogie System for Forwarders—Field Trials with TLS Data Support. Sustainability 12(16): 6412. https://doi.org/10.3390/su12166412

Uusitalo, J., Ala-Ilomäki, J., Lindeman, H., Toivio, J., Siren, M., 2020: Predicting rut depth induced by an 8-wheeled forwarder in fine-grained boreal forest soils. Ann. For. Sci. 77: 1–10. https://doi.org/10.1007/s13595-020-00948-y

Sutherland, B.J., 2003: Preventing Soil Compaction and Rutting in the Boreal Forest of Western Canada: A Practical Guide to Operating Timber-Harvesting Equipment. FERIC Advantage, 4, 1–52 p.

Toivio, J., Helmisaari, H.-S., Palviainen, M., Lindeman, H., Ala-Ilomäki, J., Sirén, M., Uusitalo, J., 2017: Impacts of timber for-warding on physical properties of forest soils in southern Finland. For. Ecol. Manag. 405: 22–30. https://doi.org/10.1016/j.foreco.2017.09.022

Uusitalo, J., Ala-Ilomäki, J., 2013: The significance of above-ground biomass, moisture content and mechanical properties of peat layer on the bearing capacity of ditched pine bogs. Silva Fenn. 47(3): id 933. http://dx.doi.org/10.14214/sf.993

Vega-Nieva, D.J., Murphy, P.N.C., Castonguay, M., Ogilvie, J., Arp, P.A., 2009: A modular terrain model for daily variations in machine-specific forest soil trafficability. Can. J. Soil Sci. 89(1): 93–109. https://doi.org/10.4141/CJSS06033

Wronski, E.B., Humphreys, N., 1994: A method for evaluating the cumulative impact of ground-based logging systems on soils. J. For. Eng. 5(2): 9–20. https://doi.org/10.1080/08435243.1994.10702656

Zemánek, T., Neruda, J., 2021: Impact on the Operation of a Forwarder with the Wheeled, Tracked-Wheel or Tracked Chassis on the Soil Surface. Forests 12(3): 336. https://doi.org/10.3390/f12030336

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