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Impact on the Operation of a Forwarder with the Wheeled, Tracked-Wheel or Tracked Chassis on the Soil Surface

Tomáš Zemánek * and Jindřich Neruda

Department of Engineering, Faculty of Forestry and Wood Technology, Mendel University in Brno, 613 00 Brno, Czech Republic; neruda@mendelu.cz

* Correspondence: tomas.zemanek@mendelu.cz; Tel.: +420-545-134-150

Abstract: The impact of a small forwarder with the wheeled chassis, tracked-wheel chassis, and tracked chassis traveling on the soil profile was studied. The three chassis types were assessed for the influence of the loading of forwarder cargo space and the degree of tire inflation on induced specific and actual pressures of tires on the soil surface. Penetrometric resistances of soil profile and rut depths in the forwarder driving track were measured. The effect of a layer of logging residues in the forwarder driving track on the size of induced actual pressures was determined. The practice of determining the impact of forest machines on the soil surface by means of a specific tire pressure does not have a full informative value. In the forwarder wheeled chassis, maximum values of actual pressures exceeded specific pressures established numerically by up to 203%. Average values of actual pressures could be reduced by 45% by reducing the pressure of tire inflation, by 70% with the use of tracks, or by 49% by traveling on the layer of logging residues. As compared with the wheeled chassis type, the tracked type of the forwarder chassis induced actual pressures to lower by 81% and the rut depth after ten forwarder passes was smaller by 50%.

Keywords: forwarder; reduced impact logging; wheeled chassis; tracked-wheel chassis; tracked chassis

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1. Introduction

The movement of forest machines across the stand results in interactions between the machine chassis and the soil surface via the contact area of wheels, tracked wheels, or tracks. From a historical point of view, the weight and performance of employed machines are increasing. Moving forest machines induce actual pressure on the soil surface, which is affected in wheeled machines mainly by tire characteristics such as diameter, width, stiffness, and degree of tire inflation. Other important parameters include tire adhesive load and components of traction forces acting on the wheel. Parameters of tires in relation to the soil environment were studied by a number of authors. Tomaraee [1], for example, studied tire rolling resistance in connection with different inflation rates and loads, Battiato and Diserens [2] dealt with the influence of load and tire inflation rate on the transmission of traction force, and Taghavifar and Mardani [3] assessed the influence of speed, tire inflation, and vertical load on wheel rolling resistance.

Soil conditions entering the interaction with the machine chassis include soil profile plasticity and elasticity, bearing capacity of soil profile, and moisture content. Alternation of seasons and weather (precipitation amount, air temperature, groundwater level) cause changes in soil moisture, thus significantly affecting soil-bearing capacity [4]. Typical soil surface in the forest environment is elastic; its elasticity being provided by roots of woody plants and herbs near the soil surface. Lower layers of soil profile can already be of plastic character. The bearing capacity of the soil body decreases very rapidly if elasticity is disturbed. Grüll [5] elaborated a decision-making scheme for passes of logging and transport machines on forest soils, which dwells on the classification of soils based on their plasticity into types of driving tracks. On the basis of soil surface changes and soil moisture, the classification recommends or prohibits the passes of machines and vehicles on specified sites, productive forest soils, and skidding lines.

A combination of the above-mentioned factors affects the way in which the pressure developed by the tire on its contact area with the soil surface is demonstrated in the soil profile. At disturbed soil elasticity, rills develop in the machine driving track in the upper layers of soil profile, which may initiate soil erosion. Very often, root systems of shallow-rooting woody plants are disturbed in these rills. Changes in soil bulk density, which immediately influence water regime and gas exchange dynamics in the soil horizon, represent a not negligible form of the impact of traveling forest machines on the soil surface. In a longer time horizon, the changes then may affect the growth of woody plants as well as the quality of assortments.

Transmission of traction forces and dynamic impacts from wheels onto the soil surface, which show particularly on steeper slopes, has a great influence on the difference in compacted soil bulk density on the slope and on flat terrain. Wheel slip, which has a great influence on the degree of compaction and disintegration of soil horizons, in connection with timber extraction up the hill is very dangerous on the slope. Time required for the regeneration of physical soil properties is very variable and dependent on the soil type. Page-Dumroese et al. [6] found out that 5 years after a logging and transport process, some soils of coarse texture renewed their bulk density in upper layers of up to 10 cm but not in deeper layers of 20–30 cm.

If the manufacturers of special forest machines provide information about the impact of supplied machines on the soil surface, the information usually includes numerically established mean specific pressures based on the tire or track unit imprint area after sinking into the natural terrain. However, if the machine moves on soils with a lower moisture content or with a higher gravel content, it is only the tire tread pattern which is in contact with the soil surface in the first travel stages, which essentially reduces the contact tire area with the soil surface and increases specific tire pressures. The action of dynamic forces on the soil surface during the machine travel is then not considered at all.

A starting point for the assessment of the impact of forest machines on the soil surface is a capability to identify all major forces acting in the interaction of the machine chassis and soil surface. Thus, it is not only about static forces, but also about the mentioned dynamic forces developing during the machine travel on the soil surface. Registration of actual pressures then demonstrates how the forces manifest in the specific conditions of a given soil profile.

Pressure in the tires of forest machines is relatively high because the wheels of these machines have to bear high loads whilst moving across uneven terrains with stumps and stones which may cause mechanical damage to low-inflated tires. One of the possible solutions are so-called tire pressure control systems (TPCS), optimizing the pressure in tires so that they correspond to actual working conditions. They allow to extend machine traction and mobility, thus enabling the machine operation in rainy weather too [7]. Sakai et al. [8] tested this strategy using an 8-wheeled Rottne Rapid forwarder with a load of 9.5 t of timber, equipped with low- and high-pressure tires with tracked wheels on coarse gravel soils with 60% of soil moisture. Research results showed that the high-pressure tires caused severe compaction in lower soil layers, and that the compaction zone caused by the loaded forwarder with tracked wheels was shallow and its in-depth degree of compaction was lower. Nevertheless, typical solutions are used for the purpose so far in the form of wide-profile tires with a possibility of lower inflation, application of tracked wheels, or employment of tracked chassis. Bygdén et al. [9] inform that tracked wheels can reduce the depth of ruts by up to 40% and Cl-Index by approximately 10%, compared with the wide-profile and low-pressure tires. On wet, soft, and shallow peat soils, Neri et al. [10] recorded, after having had reduced tire inflation rate, also a reduction of ruts from 2 to 16 cm after four forwarder passes.

Logging residues properly placed on skidding lines distribute the weight of machines to a larger area, thus reducing the pressure on the contact area in the driving track of machines [11,12]. Hutchings et al. [13] inform that a layer of logging residues cannot prevent soil surface compaction completely. However, they confirm its significance in reducing compaction on loamy soils in the stands of *Picea sitchensis* in North East England. Labelle and Jaeger [14] tested in laboratory conditions the effect of various thicknesses of layers of logging residues on the reduction of pressure on the soil surface area. Research results confirmed a reduced action of load with the use of logging residues at an amount of 10 kg/m^2, as compared with an area without the layer of logging residues. For highly susceptible soils, the authors advise a layer of logging residues 15–20 kg/m^2. The authors maintain that the layer of logging residues can gradually lose its capability to reduce pressure impacts of traveling machines with the increasing number of passes; its effect is however beneficial even at relatively high frequencies of passes (e.g., up to 12 passes). On andosols in the mixed forest stands of Northern Idaho, Han et al. [15] inform that 7–40 kg/m^2 of logging residues should be left behind as a prevention of soil compaction. Eliasson and Wästerlund [16] claim that a 10-cm layer of logging residues on the skidding lines on silt clays reduced compaction by 12.9% at a depth of 10 cm and by 4.5% at a depth of 20 cm. Ampoorter et al. [11] recorded a positive effect of the 20–30 cm layer of logging residues on the bulk density and resistance to penetration in sandy soil occurring in the pine stands of South Holland. According to the authors, a 10–20 cm layer of logging residues did not have such a favorable effect. Using the same layer of logging residues on clay-loam soils in Sweden, Elliason and Wästerlund [16] did not observe any reduction in the depth of ruts after five and more machine passes. It can be stated in summary that a complete removal of logging residues is not recommended, particularly as far as the soil cover protection against after-logging erosion is concerned [17,18]. Whole-area soil cover with logging residues is decisive in order to provide for reduced compaction of forest soils.

2. Materials and Methods

Field measurements were made in the stands of Norway spruce (*Picea abies* (L.) H. Karst.) administrated by the Training Forest Enterprise Masaryk Forest Křtiny of Mendel University in Brno. Soil type in the stand was Eutric Cambisol, soil profile moisture content ranged from 28% to 36%, longitudinal slope gradient range was from 0 to 5°, and cross slope was 0°. The measurements were taken on basic operating variants of the machine with the wheeled chassis (Figure 1a), tracked-wheel chassis, and tracked chassis (Figure 1b). The wheeled version of the forwarder was equipped with wheels with dimensions 400/60–15.5, and the tracked version was equipped with rubber tracks of 0.45 m in width with a steel insert. Measurements for the wheeled forwarder variant were further divided according to the inflation of front and rear axles (150, 250, and 350 kPa). Measurements for the tracked chassis variant were divided into two variants according to the level of pressure in the tensioning system of tracked chassis tracks (10.000 and 14.000 kPa).

Curb weight of the wheeled forwarder was 6220 kg. Upon the assembly of tracks on all tandem axles, the machine curb weight increased to 7120 kg. The curb weight of the forwarder tracked chassis version was 9670 kg. Two variants of cargo space load were then measured in all forwarder chassis versions (without load and with a load of 4185 kg, 5-m long spruce logs).

Specific pressures of forwarder tires and tracks on the soil surface were determined numerically. In the terrain, actual pressures in the soil profile induced by machine passes, penetrometric resistances of soil profile, and depths of ruts in the forwarder driving track were measured for the above-mentioned forwarder variants.

Specific pressures of the forwarder on the soil surface were determined for three variants of inflation of tires on the front and rear axles in the wheeled chassis and for two variants of pressure level in the tensioning system of tracks in the tracked chassis according to Equation (1):

$$ps = G_k/S \text{ [kPa]} \quad (1)$$

where ps—specific pressure of tires [kPa], G_k—wheel load [kN], S—contact area of tire tread with the soil surface [m^2].

(**a**) (**b**)

Figure 1. (**a**) Forwarder with the wheeled chassis; (**b**) forwarder with the tracked chassis.

Contact areas of individual forwarder wheels at the given tire inflation were determined experimentally by tire tread imprint on a large sheet of paper on the solid mat. Then, the outer boundaries of imprints were placed in a rectangle, and the area of this rectangle was considered as a simulation of the contact area of machine wheel with the soil surface after the sinking of tire tread pattern into the soil profile (Figure 2). This procedure was repeated five times and the resulting average value was determined as the arithmetic mean. In the case of tracked chassis and tracked-wheel chassis, the contact area was determined as a product of track width and track active length.

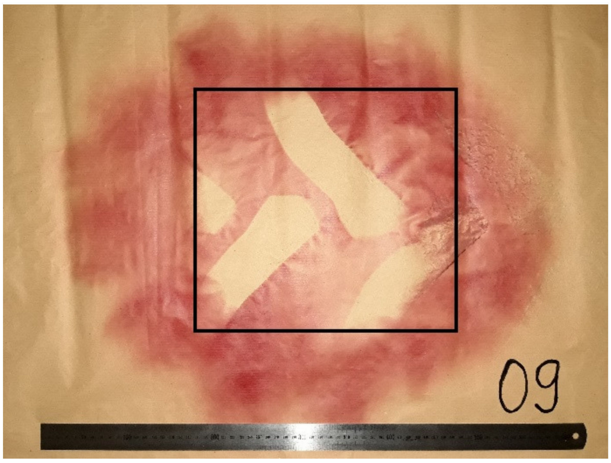

Figure 2. The outer boundaries of the tire tread imprint, front axle, tire inflation 250 kPa, load 0 kg.

Actual pressures in the soil were measured by a measuring device (Figure 3) with the pressure sensor consisting of a strain gauge connected with a pressure probe, recording unit MultiHandy 3020 and notebook with the software for data processing. The pressure probe (flexible plastic container of cylindrical shape with a diameter of 30 mm and length of 140 mm) was connected to the strain gauge by means of a reinforced rubber hose. The whole closed system was filled with liquid and deaerated. By this, a homogeneous hydraulic connection was created, through which the soil pressure on the pressure probe walls was transmitted onto the measuring strain gauge type P8AP made by HBK (Hottinger Brüel & Kjaer GmbH, Darmstadt, Germany) with a range of measured pressures from 0 to 1000 kPa (measurement accuracy class of 0.3). The strain gauge was interconnected with the recording unit. The frequency range of measurement (sampling frequency) was set to

10 samples per second. Prior to the measurement, accuracy of the measuring device was calibrated by loading the pressure probes with a defined load, subsequent reading of the pressure value, and its comparison with the numerically established result. It was found that the measurement error reached max. 4%, which appeared fully sufficient with respect to the purpose of the measurement.

Figure 3. Measuring device for the determination of actual pressures in the soil profile during machine passes.

During the measurement, the pressure probes were placed into the soil profile at a depth of 15 cm. The depth of 15 cm was chosen because the soil layer features a considerable amount of roots of shallow-rooting woody plants [19], which are exposed to potential damage when the soil is loaded by passing forest machines. A soil pit was dug out from the side of the assumed machine driving track. A horizontal hole was drilled in the soil pit front at the required vertical depth, whose length occupied the entire width of the assumed machine driving track. A pressure probe was pushed into the hole so that its transverse axis would be identical with the longitudinal axis of the assumed machine driving track; the remaining part of the hole was then sealed with earth, and before the beginning of measurements, the whole soil pit was covered with earth and compacted.

There were 10 continuous passes (five forward and five reverse) in one driving track realized gradually with each forwarder chassis version. Five replicate measurements were carried out in the same conditions. During the measurement, the forwarder was moving at a speed of up to 5 km/h. If the machine deviated from the travel direction by more than 10 cm, the whole series of ten passes over the new soil pit was repeated. Soil profiles used for measuring actual pressures were only those whose compaction did not exceed 1.3 MPa at a depth of 15 cm before the forwarder pass. During each pass, the maximum reached actual pressures of the given chassis type were determined. The resulting average value of actual pressures in the series of ten forwarder passes was determined by using the median. The data series were evaluated by the Kruskal–Wallis test and by the Wilcoxon signed-rank test. The results were determined with 95% confidence.

During the measurement of actual pressures induced by forwarder passes on the layer of logging residues, the layer thickness ranged from 35 to 45 cm and the layer was laid 2 m before and 2 m behind the soil pit in the longitudinal axis of the assumed machine driving track (Figure 4). To prevent the machine tilting and, hence, a change in weight distribution onto the left and right part of the measured axle, an identical layer of logging residues was placed also into the other driving track where the measurements were not made. The effect of the logging residues layer on the induced actual pressures was compared only in the case of chassis variants, where the highest actual pressures were recorded. The following measurement variants were included in the comparison: wheeled chassis with the load and tire inflation of 350 kPa, tracked-wheel chassis with the load, and tracked chassis with the load and pressure in tensioning system of tracks of 14,000 kPa.

Figure 4. Preparation of logging residues into the assumed machine driving track.

Soil profile moisture content was measured by the moisture meter Delta-T HH2 (Delta-T Devices Ltd, Cambridge, UK) in five replicates at one measuring point. The resulting value was determined as an arithmetical mean of five measurements. Measuring tips were manually calibrated by using a metal template after each series of measurements.

Soil profile compaction was measured by using the penetrometric method with the Eijkelkamp Penetrologger (Eijkelkamp Soil & Water Nijverheidsstraat, Giesbeek, The Netherlands). The measurement had, at all times, five replicates before the machine pass in the assumed forwarder driving track and then after each pass of the machine. The resulting value was determined as an arithmetic mean of the five measurements.

Driving track depth was measured after each forwarder pass to the nearest centimeter. Soil profile moisture content was 32.3%. The measurement was related to the lower edge of an auxiliary measuring rod, which was placed perpendicularly to the longitudinal axis of the deepening forwarder driving track at the level of the original soil surface.

3. Results and Discussion

Information about the total contact area of the respective forwarder chassis variants with the soil surface, specific, and maximum actual pressures on the front and rear axles in dependence on cargo space load and rate of tire inflation or pressure level in the tensioning system of tracks is given in Tables 1–3.

Table 1. Specific pressures of a wheeled forwarder on the soil surface and actual pressures at a soil profile depth of 15 cm.

	Tire Inflation [kPa]	Overall Contact Area of Machine with Soil Surface [m^2]	Specific Pressure (Front/Rear Axle) [kPa]	Maximal Actual Pressures Reached (Front/Rear Axle) [kPa]
Load 0 kg	150	0.64	102/86	124/99
	250	0.50	135/108	155/114
	350	0.38	170/147	201/159
Load 4185 kg	150	0.85	108/133	197/271
	250	0.57	150/199	275/388
	350	0.51	182/220	326/437

Differences in the contact area of tires with the soil surface in the front and rear axle of the wheeled forwarder were about 40% at minimum and maximum inflation (the same in the measurement variants with or without load). The unloaded wheeled forwarder showed differences between the contact areas of the front and rear axles in the order of units of percent, but when the cargo space was loaded with the set weight, the differences were up to 66%, according to the variant of tire inflation. The front axle of the loaded wheeled forwarder contributed to the total machine contact area by ca. 25% depending on the degree of tire inflation. In practice, this fact means that if the tires are inflated to 150 kPa, ca. 22% of total machine weight falls onto the front axle, which may lead to impaired maneuverability of the forwarder in difficult terrain, driving up the hill in particular. In the Czech Republic, Decree no. 209/2018 Sb. [20] stipulates that at least 20% of the total weight of the vehicle must fall onto the front driven axle of a motor vehicle. The Decree no. 209/2018 Sb. is based on the EU Council Directive 96/53/EC [21] and Directive 2015/719 of the European Parliament and of the Council [22]. The use of tracked wheels increased the total contact area of the wheeled variant of the forwarder with the soil surface by more than four times (in the variants of measurement with and without loads). If the forwarder moves on a solid base, only individual segments of track tread pattern are in contact with the soil surface and the total contact area is smaller by 59% than in the case when the segments sink into the plastic soil surface and an entire area of the track is in contact with the soil surface. Pressure adjustment in the tensioning system of tracks in the tracked chassis version alter the total contact area of a loaded machine with the soil surface by up to 18%. Differences between the contact area of the front and rear axles in the tracked machine version were not so conspicuous, as compared with the wheeled version (max. 45%). Thanks to its design, the tracked chassis of the loaded forwarder was more flexible in changing the contact area with the soil surface (according to the level of pressure in the tensioning system of tracks by up to 50%), as compared with the use of tracked wheels.

Table 2. Specific pressures of a wheeled forwarder with tracked wheels on the soil surface and actual pressures at a soil profile depth of 15 cm.

	Tire Inflation [kPa]	Overall Contact Area of Machine with Soil Surface [m^2]	Specific Pressure (Front/Rear Axle) [kPa]	Maximal Actual Pressures Reached (Front/Rear Axle) [kPa]
Load 0 kg	350	1.68	46/39	82/70
Load 4185 kg	350	2.05	48/61	105/132

Table 3. Specific pressures of a tracked forwarder on the soil surface and actual pressures at a soil profile depth of 15 cm.

	Pressure in Tensioning System of Tracks [kPa]	Overall Contact Area of Machine with Soil Surface [m^2]	Specific Pressure (Front/Rear Axle) [kPa]	Maximal Actual Pressures Reached (Front/Rear Axle) [kPa]
Load 0 kg	10,000 14,000	1.72 1.34	57/55 80/65	101/90 131/105
Load 4185 kg	10,000 14,000	2.39 2.02	57/56 72/63	114/98 146/116

The numerically established specific pressures were the highest in the wheeled version of the forwarder. Depending on the cargo space loading with weight and degree of tire inflation, the specific pressures ranged from 86 kPa (cargo space without load, tire inflation 150 kPa, rear axle) to 220 kPa (cargo space with load, tire inflation 350 kPa, rear axle). In the variant of measurement with the load, the induced specific pressures could be reduced by nearly 90 kPa through tire inflation on the wheeled forwarder rear axle. Differences between the induced specific pressures of the front and rear axles were by order the same in both variants of cargo space loading—on average 19%. In the case of the forwarder without a load, higher specific pressures were recorded on the machine front axle, and in the case of the forwarder with a load it was vice versa. When the rear axle of the wheeled forwarder was loaded with weight, its specific pressure increased on average by 26% according to tire inflation. When the tracked wheels were used, the induced specific pressures of the wheeled forwarder with a load on both axles were reduced by more than 3.5 times. Compared with the wheeled chassis, specific pressures of tracked forwarder chassis exhibited less variance. When the cargo space was loaded with weight, the contact area of track units with the soil surface increased and specific pressures remained the same or close to values without the load. The established specific pressures ranged from 55 to 80 kPa and were higher on the machine front axle. With the pressure of 10,000 kPa in the tensioning system of tracks, the difference between the induced specific pressures of the front and rear axles in the tracked forwarder was only in units of percent. When the pressure in the tensioning system of tracks was increased to 14,000 kPa, the specific pressure on the front axle of the loaded machine increased by ca. 26%.

In connection with the induced specific pressures of the tracked chassis, a difference should be pointed out between the point load of individual wheels of the forwarder track units and the values converted to the entire contact area of the tracked unit. It followed from the measurements that two middle wheels of the front and rear track units of the loaded forwarder are loaded many times more than side wheels. In this sense, the specific pressures of two middle wheels exceed the values of specific pressures converted to the entire contact area of the tracked unit in the order of tens of percent. For example, at a level of pressure in the tensioning system of tracks of 14,000 kPa, specific pressures converted to the contact area of the whole track unit were exceeded on the second wheel of the front tracked unit by more than twice. The different point loading of individual wheels of tracked units analogically shows also in the recorded actual pressures. In the case of tracked wheels, the situation was similar; within the active length of the tracked wheel, a higher point loading being recorded under the wheels than under the part of the track tensioned between them.

Actual pressures induced on the soil surface by the traveling forwarder exceeded the numerically established specific pressures in all cases. In the case of average values of actual pressures, these exceeded the specific pressures by up to 175% in the wheeled chassis, by up to 192% in the tracked-wheel chassis, and by up to 137% in the tracked chassis (Figure 5). Taking into account the maximum values of actual pressures reached, exceeding the values of specific pressures were even higher—by up to 203% in the wheeled chassis and tracked chassis, and by up to 218% in the tracked-wheel chassis. The tracked-wheel chassis exhibited the highest values of exceeded specific pressures, both average and maximal ones. The fact is probably associated with the inappropriately designed methodology for establishing the contact area of the tracked-wheel chassis with the soil surface and with the uneven distribution of machine weight on the entire area of tracked wheels (different loading in sections under wheels and between the wheels). When the cargo space of the wheeled forwarder was loaded with a weight, actual pressures recorded on the front and rear axles during the machine travel were higher by 142% and by 283%, respectively. The different tire inflation in the wheeled chassis (150 kPa and 350 kPa) of the loaded forwarder succeeded in reducing the induced actual pressures by up to 45%. The range of reached maximum actual pressure values was from 99 kPa on the rear axle of the forwarder without load up to 437 kPa on the rear axle of the machine with a load, according to the degree of tire inflation.

As compared with the wheeled chassis, the use of tracked wheels reduced the average values of induced actual pressures at the same cargo space loading by 2.9 times on the front axle and by 3.4 times on the rear axle of the forwarder. The cargo space loading did not manifest in the change of average actual pressures so much as in the wheeled chassis with the increase on the front axle being 115% and on the rear axle 169%. The wheeled and tracked-wheel chassis variants of the forwarder exhibited higher actual pressures on the rear axle, while the situation in the tracked chassis variant was reversed.

With the same load, the tracked chassis exhibited the lowest actual pressures, although the tracked forwarder version had the highest curb weight. The range of recorded actual pressures was from 90 kPa (pressure in the tensioning system of tracks 10,000 kPa, rear axle, without load) to 146 kPa (pressure in the tensioning system of tracks 14,000 kPa, front axle, with load). Compared to the wheeled chassis, average actual pressures recorded on the front and rear axles were 3.4 times and 5.3 times lower, respectively. When the cargo space was loaded, actual pressures induced by traveling increased only by about 10% on both axles. In line with the numerically established specific pressures, maximum values of actual pressures were recorded also on the two middle wheels of the forwarder track units.

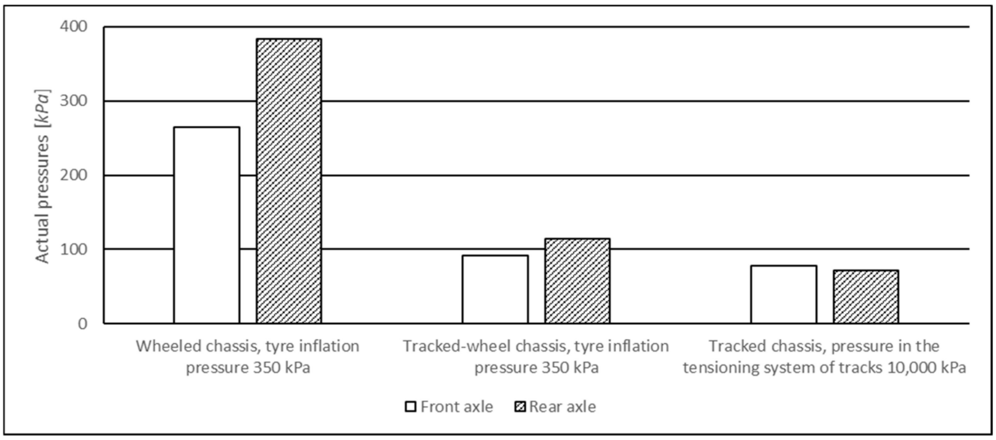

Figure 5. Average induced actual pressures in the respective chassis variants of the loaded forwarder.

The course of induced actual pressures of rear axles in the respective forwarder chassis variants with the load was evaluated by Kruskal–Wallis test. Statistically significant differences were found between wheeled and tracked-wheel chassis and between wheeled and tracked chassis, *p* value 0.013872, respectively 0.000005, box plot Figure 6. No statistically significant difference was found between tracked-wheel chassis and tracked chassis.

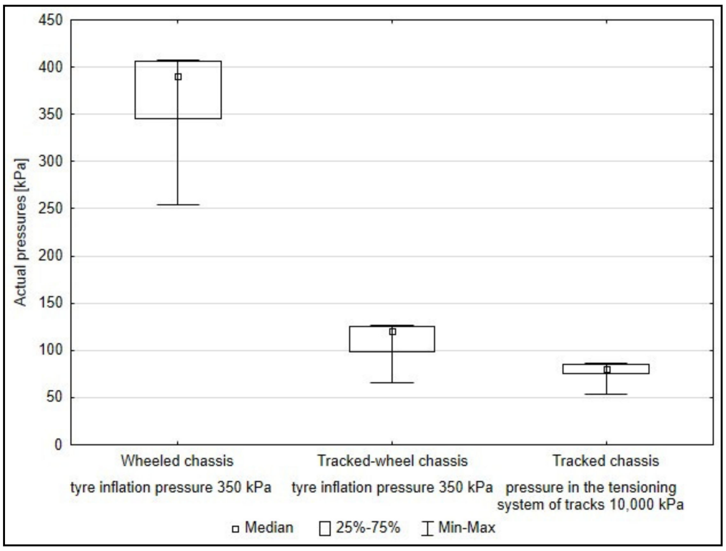

Figure 6. Range of values of induced actual pressures of rear axles in the respective forwarder chassis variants with the load during the first 10 passes.

The trend in the course of actual pressures induced by the forwarder travel and measured in the soil profile was increasing with the increasing number of passes; from about the sixth pass, the increase slowed, or a slight decrease followed (Figure 7).

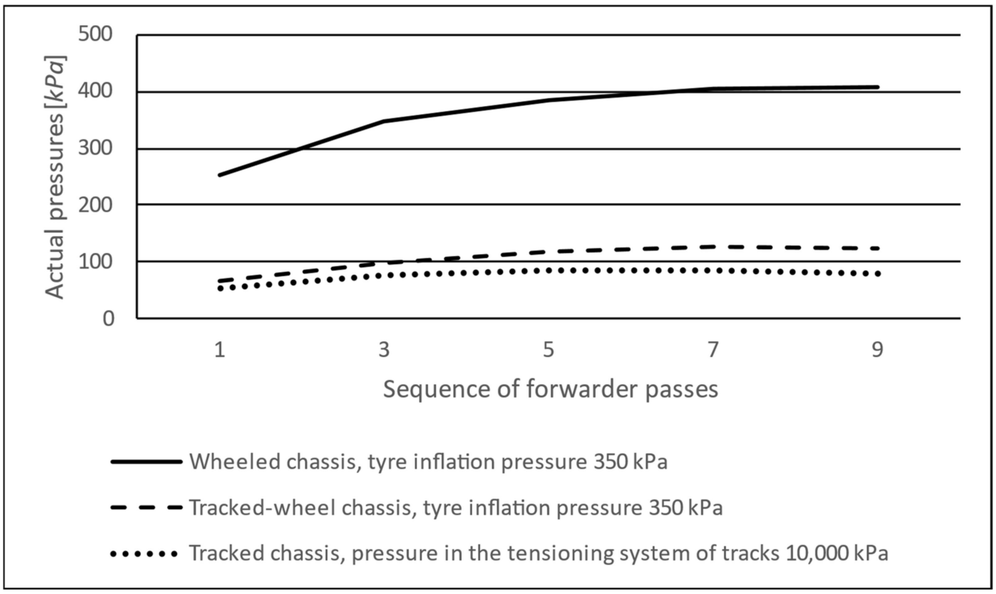

Figure 7. The course of induced actual pressures of rear axles in the respective forwarder chassis variants with the load during the first 10 passes.

The layer of logging residues had a positive influence on reducing the actual pressures induced in the machine driving track in all chassis variants (Table 4). On the layers of logging residues from 30 to 45 cm, the level of induced actual pressures at a soil profile depth of 15 cm was reduced at repeated measurements for the wheeled chassis by up to 49%, for the tracked-wheel chassis by 23%, and for the tracked chassis by 11%. In these cases, the maximum values of actual pressures did not exceed 230 kPa. Depending on the chassis type, the layer of logging residues was, after 10 passes, compacted to 44–63% of the initial thickness.

Table 4. Actual pressures of the three loaded chassis variants at a soil profile depth of 15 cm when driving on a layer of logging residues.

	Tire Inflation [kPa]	**Pressure in Tensioning System of Tracks [kPa]**	**Maximal Actual Pressures Reached (Front/Rear Axle) [kPa]**
Wheeled chassis	350	-	183/224
Tracked-wheel chassis	350	-	84/102
Tracked chassis	-	14,000	130/105

The impact of logging residues on the induced actual pressures was verified by the Wilcoxon signed-rank test. Statistically significant differences were found for wheeled, tracked-wheel, and also for tracked chassis; p values 0.005062, 0.005051, and 0.007686.

To achieve a sufficient effect, the thickness of the layer of logging residues prior to compaction should be at least 40 cm (Ampoorter et al. [11] recommend 20 to 30 cm). We found that this layer thickness corresponds, on average, to a weight of 55 kg of logging residues per 1 m^2 (Labelle and Jaeger [14] recommend 15–20 kg/m^2, Han et al. [15] recommend 7–40 kg/m^2). Differences in the obtained results reflect different conditions of measurement, namely differences in soil types and soil profile moisture contents. The use of logging residues for the efficient reduction of induced actual pressures of forest machines is often limited by site conditions or by intended use of residues for energy purposes.

As to the methodology for measuring actual pressures, it should be pointed out that the pressure probe had to be placed precisely in the longitudinal axis of the presumed machine driving track. If the machine deviates from the travel direction by more than

10 cm at repeated passes, pressures induced on the soil surface decrease considerably. On the other hand, it follows that, passing repeatedly along the same route without strictly adhering to the driving track, roots in the same place are not exposed repeatedly to the adverse impact of pressures.

Repeated forwarder passes induce soil surface compaction. The highest increase in the soil profile compaction was recorded in the wheeled forwarder with the tire inflation of 350 kPa. After the sixth machine pass, penetration soil resistance recorded at a soil profile depth of 15 cm was ca. 280% of the initial value. The increase recorded at a soil profile depth of 40 cm was lower—ca. 170%. In the middle category forwarder with a double load weight, Sakai et al. [8] observed a severe compaction also in the lower layers of the soil profile. The different results can be, in our case, explained by the different soil type with a lower share of gravel and a nearly twice-lower soil profile moisture content. Our former measurements indicate that forwarders of middle categories are fully comparable with small forwarders regarding the size of specific and actual pressures induced on the soil surface. The higher total weight of these machines is compensated by the larger contact area of tires with the soil surface. In the tracked-wheel forwarder variant, a decreased rate of the increasing soil profile penetration resistance was recorded after the sixth machine pass, too. After this machine pass, the soil profile penetration resistance exhibited ca. 240% of initial value before the passes. In the tracked forwarder, a slowed increase of soil profile penetration resistance was recorded only after the eighth machine pass on the layer of logging residues. After this pass, the value of soil profile penetration resistance amounted to about 190% of initial value before the passes.

Figure 8 illustrates the increasing soil profile penetration resistance after the third and the sixth pass of the wheeled forwarder with the load of 4185 kg on the Eutric Cambisol soil type. Our measurements showed that the soil profile penetration resistance was increasing during the first six passes of the wheeled forwarder; then the trend of increasing values of the penetration resistance of the soil profile was not so intensive (Figure 9). Our results can be compared with the results of other authors who report the boundary of essential changes in the bulk soil density, e.g., after the eighth pass [8,23], after the fifth pass [24], after the fourth pass [25], or after the second pass [26], in dependence on the soil type and current conditions, soil profile moisture content in particular. The greatest changes in the soil profile penetration resistance were recorded at depths from 10 to 40 cm.

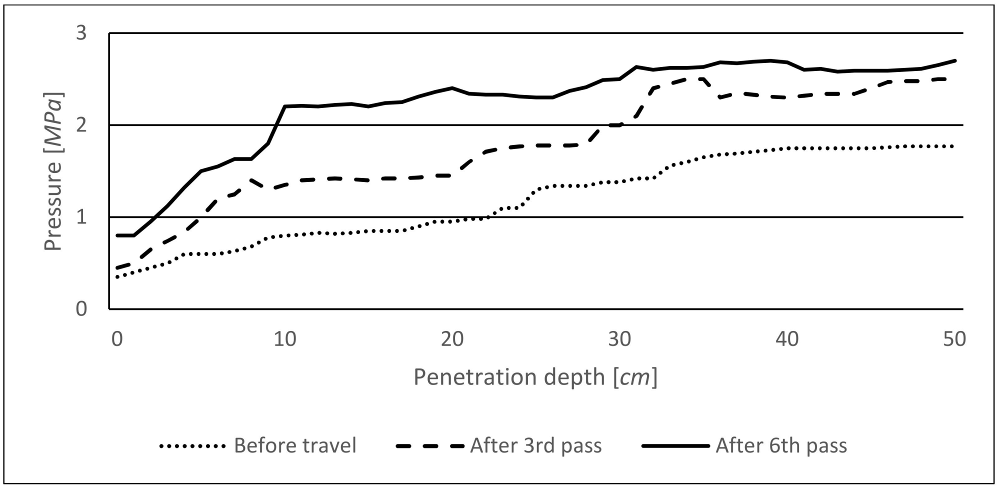

Figure 8. Soil profile compaction before travel, and after the third and sixth pass of the loaded wheeled forwarder.

Differences among the tested chassis types showed also in the degree of driving track deepening after the repeated forwarder passes. Figure 10 illustrates the development of rut depth in the loaded forwarder with the wheeled, tracked-wheel, and tracked chassis types. The maximal rut depth after the tenth pass was reached in the wheeled forwarder variant (34 cm). A more intensive deepening of the rut occurred in the soil profile after the fifth pass of the forwarder wheeled chassis. At that moment, the upper layer elasticity was probably disturbed in the soil profile. On wet, soft, and shallow peat soils, Neri et al. [10] recorded, after having reduced the tire inflation degree, also a depth of ruts reduced by 2–16 cm after four passes of the forwarder. In our conditions, we recorded a reduced depth of the ruts, rather on the lower boundary of this interval, after having reduced pressure in standard tires by 100 kPa. The increased contact area of the forwarder with the soil surface by using tracked wheels positively showed in the depth of the rut, which was by more than 20% lower (27 cm) after the tenth pass of the tracked-wheel chassis. Bygdén et al. [9] state that, compared with the wide and low-pressure tires, tracked wheels can reduce the depth of ruts by up to 40%. Compared with the standard tires of 400 mm in width, we recorded ca. half values in our conditions. The rut depth was lower by half (17 cm) after the tenth pass of forwarder tracked-wheel chassis, as compared with the wheeled forwarder chassis. In the tracked chassis of the forwarder, elasticity of the upper layer of soil profile was disturbed and the intensity of rut depth increased after the eighth pass only.

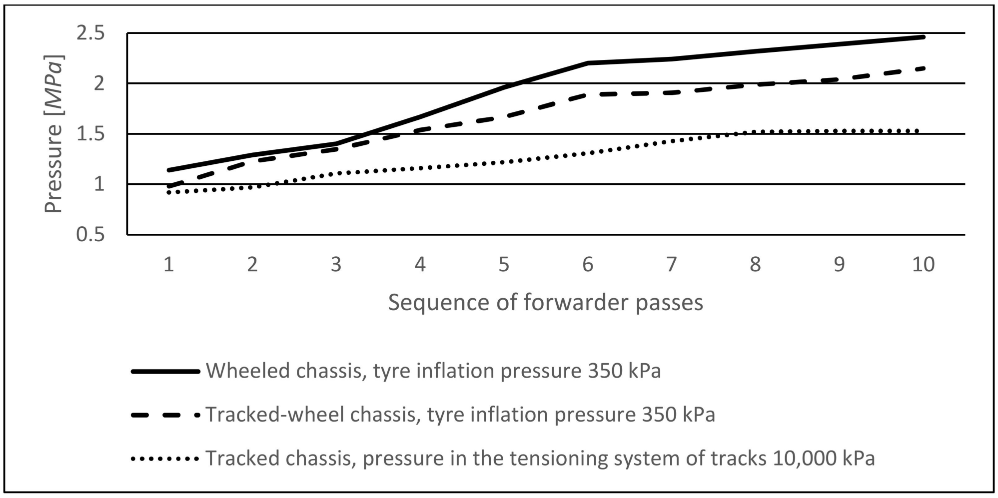

Figure 9. Soil profile compaction at a depth of 15 cm during ten passes of three chassis variants of the loaded forwarder.

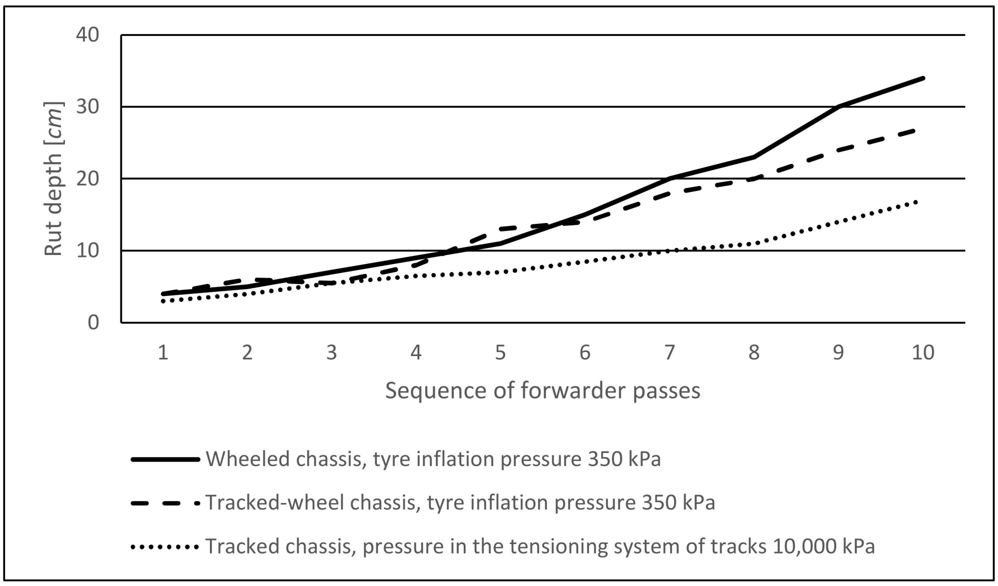

Figure 10. Driving track deepening in the soil profile after the pass of wheeled, tracked-wheel, and tracked type of the loaded forwarder.

4. Conclusions

Our findings indicate that the established practice of determining the impact of forest machines on the soil profile by specific tire pressure does not have a full informative value. Higher pressure values were reached both by the numerical determination of specific pressures with the point load on individual wheels of tracked or tracked-wheel units, and at the measurement of induced actual pressures in the natural soil profile during repeated machine passes.

Maximum values of actual pressures reached in the wheeled chassis of the forwarder exceeded the numerically determined specific pressures by up to 203%. In practice, the average values of actual pressures could be reduced by 45% by reducing the tire inflation pressure, using tracks by 70%, or driving on a layer of logging residues by 49% in the monitored wheeled forwarder with load.

Compared with the wheeled chassis version, the tracked chassis of the loaded forwarder induced actual pressures lower by 81%, and the rut depth after ten passes was less by 50%.

Substantial soil profile compaction occurred in the wheeled and tracked-wheel forwarder chassis types after the sixth pass, and in the tracked chassis it was after the eighth pass only.

In line with the requirement for reducing actual pressures induced by the forwarder chassis, we can recommend the tracked-wheel version out of the three monitored chassis types. Compared with the tracked chassis type, the tracked-wheel chassis provides greater flexibility of the forwarder when moving in the terrain, while being technically simpler and less costly. Actual pressures induced on the soil profile are similar.

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