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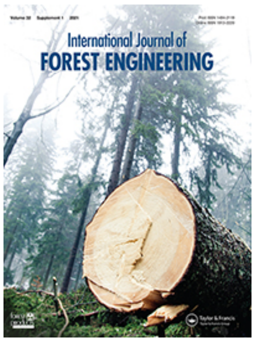

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The effect of bogie track and forwarder design on rut formation in a peatland

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ABSTRACT
The effect of forest machinery on the rut formation on extraction trails is an important aspect of forest operations. The aim of this study was to compare how track design and vehicle configuration affects rut formation on straight and curved test trails with no slash mats on peatland. Rut depth was observed from five machine-track combinations on several test plots after several passes and two different trail configurations, straight and curve. The observations (N = 760) were modeled using a mixed model approach to include the variation between the combinations. The results show that rut depth decreases exponentially with soil shear modulus, increases linearly with the number of passes and is not affected with the trail section configuration. The overall coefficient of determination is $R^2 = 0.55$. A first generation Ponsse Elk with Fomatec tracks (EFwo) showed the lowest rut formation, followed by a first generation Ponsse Elk with Fomatec tracks equipped with add-on track shoes (EFw), a Ponsse Buffalo with KOPA high flotation tracks (Kopa) and a Ponsse Elk 10 W with Olofsfors mixed tracks (E10W), while a Ponsse Elk with long wheelbase bogie and Olofsfors high-flotation tracks (LWB) showed the deepest rut formation. Vehicle dynamics on peatlands are still far from being fully understood and the paper highlights the complexity of the interactions of the variables studied while providing a valid modeling tool with applications in planning of forest operations and simulation.

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Trafficability; mobility; peat shear modulus; steel tracks; 10-wheeled forwarder; long wheelbase bogie

Introduction

The emerging trends on green bioeconomy, resulting in higher levels of wood mobilization from the forests, are strongly dependent on the supply of sustainably produced timber (Roos et al. 2013). As a result, the relevance of forwarding timber from sensitive areas with soft soil is becoming more apparent (Keskitalo et al. 2016), particularly on peatlands, which are rather common in Northern Europe: especially in the Nordic countries (Finland, Sweden, Norway), Baltic countries (Estonia and Latvia) and across Russia (Päivänen and Hånell 2012). In addition, peatland forestry is of importance in the United Kingdom, Ireland, Canada, and the United States (Minkkinen et al. 2008).

The aim of draining peatlands for forestry is to increase growing stock and thus raw material production for the forest and wood products industry. It has been estimated that around 15 million ha of peatlands have been drained for improving conditions for forest growth in the boreal and temperate zones during the last century (Päivänen and Hånell 2012). In Finland, more than 20% of the harvesting potential is on peatland forests, where solutions for harvesting during the non-frozen period are needed.

Concerning harvesting operations, peatlands present important challenges. In drained peatlands, the thickness of the top layer incorporating plant roots is only 10 to 20 cm (Laiho and Finér 1996). The porosity of peat is high, easily leading to high water content (Päivänen 1973). From the soil strength point of view, the top layer with considerable tensile strength provided by roots of trees and shrubs is essential, the supporting function of the decomposed peat being of secondary importance (Ala-Ilomäki 2006). The strength of the top layer is subject to the variation of density and species of the vegetation, resulting in extreme spatial variation in trafficability (Ala-Ilomäki 2006), as the soil strength and displacement during machine operations are strongly affected by the top layer of peat, the root systems in the area and the presence of slash mats (Uusitalo and Ala-Ilomäki 2013).

Therefore, soil type, stoniness, soil moisture and vegetation-related root mass, among others, play an important role in the trafficability of machinery (Suvinen 2006, Campbell et al. 2013; Uusitalo and Ala-Ilomäki 2013; Niemi et al. 2017). The ditch network formed by individual drainage ditches constitutes a hindrance to vehicle mobility and extraction trail planning, and the average primary transportation distance is generally double that of stands with mineral soils (Sirén and Tanttu 2001). Low soil strength is, however, the most significant factor affecting timber harvesting and forwarding, as it means higher risk for soil displacement and compaction when exposed to heavy machinery traffic (Labelle and Jaeger 2011; Goutal et al. 2013; Klaes et al. 2016). Soils with high moisture content, in textured soils and peatlands are therefore sensitive to soil damage and compaction (Sirén et al. 2013; Uusitalo and Ala-

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Ilomäki 2013). Mechanized forest operations can cause detrimental impacts on the environment through soil rutting and compaction, especially when forest trafficability conditions are not optimal and soil strength is low (Vega-Nieva et al. 2009; Murphy et al. 2009; Labelle and Jaeger 2011; Duncker et al. 2012; Goutal et al. 2013; Sirén et al. 2013; Uusitalo and Ala-Ilomäki 2013; Niemi et al. 2017). Rut formation in forestry may cause soil damage as well as root damage to the remaining trees. Severe soil compaction causes reduced growth of the trees growing in such conditions (Kozlowski 1999).

Concern for soil and root disturbances through forest operations has increased in parallel to the trend toward larger, heavier, and more powerful forest machinery in the past decades (Hartanto et al. 2003; Ala-Ilomäki et al. 2011). The size and mass of machines have increased, and today the typical mass of forwarders and harvesters is close to 20 tons (Sirén et al. 2018). In addition to popular eight-wheeled harvesters and forwarders, a ten-wheeled forwarder has been introduced as a concept of a machine with lower nominal ground pressure (Ala-Ilomäki et al. 2011). In addition to vehicle mass, vehicle configuration and ground pressure play an important role. Ala-Ilomäki et al. (2011) found modern forwarders more favorable in terms of rut formation compared to a considerably lighter forwarder from the 1980s. Equipping a wheeled forwarder with bogie tracks lowers nominal ground pressure (NGP) and can reduce rut formation by up to 40% (Bygdén et al. 2003). In recent years, track development has been active, and specialized tracks have been developed for different soil conditions (Sirén et al. 2018). Previous studies have shown that the use of bogie tracks can reduce sinkage when compared to bare wheels (Gerasimov and Katarov 2010), reduce the peak loads (Labelle and Jaeger 2019) and consequently reduce rut depth (Sakai et al. 2008). Haas et al. (2016) compared rut formation caused by different tires and bogie tracks, finding 940 mm wide tires a viable possibility to reduce rut formation.

Considerable development work has been done in this field (Högnäs 1997; Ala-Ilomäki et al. 2011), and bogie tracks have played an important role in reducing rut formation. Minimizing the risk of soil rutting in mechanized forest operations still requires careful timing, route planning and selection of harvesting equipment (Ala-Ilomäki et al. 2011; Solgi et al. 2016), and there is a need to investigate the effects of the most recent developments in track and forwarder designs on rut formation on soft soils. In this context, the aim of this study is to investigate the effects of different models of bogie tracks and vehicle design on rut formation on peatlands.

Materials and methods

Study and test trail design

To determine the effect of bogie track type and vehicle configuration on rut formation, a field study was conducted in late June 2019 in Rautavaara, Eastern Finland (63°22′N, 28°35′E in WGS84). Straight and curved test trails were designed on a Scots pine (*Pinus sylvestris*) dominated, drained peatland. The straight test trails were 20 m long and 4 m wide, divided into four 5-m long test plots. The radius of the 4 m wide curved trails was 20 m, and they covered a turn of 90°. The curved trails were not subdivided into test plots. The pairs of test trails were located so that the forwarders could travel from the straight trail to the curved one without sharp turns and obstruction or damage to other trail paths. The trails were cut prior to the test with the harvester working from outside the test trails, so that the soil and tree roots on the test trails were left intact. Felled trees were processed outside the test trails, so there were no slash mats on the trails.

The forwarders were driven loaded with approximately 5,100 kg of pulpwood with an average length of 4.56 m. The same load was used and transferred between all machine-track combinations (hereinafter: machines). The load size was determined by the forwarder operator used in the first test, who was instructed to choose a load size that would enable three to four passes on each trail with minimal risk of bogging down.

Each machine was randomly allocated to a specific study trail pair, each consisting of a straight and a curved trail. Each machine conducted three to four passes on each trail. Rut depth was measured manually with a horizontal laser level and a surveyor's measuring rod at three points (1.25 m, 2.50 m and 3.75 m) on each 5 m segment of the study plot on the straight trails and at seven points (2 m intervals) on the curved trails. Measuring points were marked with spray paint in the wheel track on the peat surface to enhance consistency in measurement location accuracy during the passes. Rut depth was measured at the deepest point of the rut, which was usually a track shoe depression in peat.

Studied forwarders and tracks

The studied forwarders and tracks were (abbreviation used in the latter given in parentheses):

- Eight-wheeled Ponsse Elk with long wheelbase on the rear bogie, equipped with Olofsfors Baltic (front) and Olofsfors Magnum (rear) tracks (LWB)
- First generation 8-wheeled Ponsse Elk, equipped with Fomatec Rud Combino Hybrid tracks (EFwo)
- First generation 8-wheeled Ponsse Elk, equipped with Fomatec Rud Combino Hybrid tracks with added track shoes (EFw)
- 8-wheeled Ponsse Buffalo, equipped with KOPA Flotation tracks (Kopa)
- 10-wheeled Ponsse Elk, equipped with Olofsfors Eco Soft (front) and Max-Magnum (rear) tracks (E10W)

The specifications of the studied machines are presented in Table 1. The machine in-test mass includes the estimated load mass and the forwarder and track mass provided by the manufacturers. Track width, track shoe length and spacing were measured in situ. Track shoe coverage was determined as the share of the area covered by the track shoes divided by the total area of the track shoes and the empty spaces between them. In other words, the lower the shoe coverage, the lower the share of ground contact area in contact with the shoes. Nominal ground pressure (NGP) was calculated according to Malmberg (1981). The nominal ground pressure divided by track shoe coverage (NGP_{adj}) is also provided for better description of the average pressure acting under the track shoes. The differences in

Table 1. Specifications of studied machines. In-test mass includes load and tracks.

	Studied machine				
Machine feature	LWB[1]	EFwo[2]	EFw[3]	Kopa[4]	E10W[5]
Year of manufacture	2017	2013	2013	2016	2017
Bogie wheelbase, mm					
Front	1500	1500	1500	1500	1500
Rear	1890	1500	1500	1500	2910
Mass loaded, kg					
Front	13,449	12,290	13,290	15,396	13,140
Rear	15,551	15,160	16,160	16,204	17,560
Total	29,000	27,450	29,450	31,600	30,700
Track type front	Olofsfors Baltic	Fomatec Rud Combino Hybrid w/o add-on shoes	Fomatec Rud Combino Hybrid with add-on shoes	KOPA Flotation	Olofsfors Eco Soft
Track type rear	Olofsfors Magnum	Fomatec Rud Combino Hybrid w/o add-on shoes	Fomatec Rud Combino Hybrid with add-on shoes	KOPA Flotation	Olofsfors Max-Magnum
Track width, mm					
Front	790	840	850[6]	900	900
Rear	930	840	850[6]	900	910
Track mass, kg					
Front	2000	1100	1600	2150	1700
Rear	2350	1100	1600	2150	2300
Track shoe coverage, %					
Front	69	31	70	91	49
Rear	69	32	71	91	44
NGP, kPa					
Front	73	63	67	74	63
Rear	61	78	82	78	51
NGP_{adj}, kPa[7]					
Front	106	203	96	81	128
Rear	89	243	115	85	117

[1] LWB = Ponsse Elk with long wheelbase bogie and Olofsfors high-flotation tracks, [2] EFwo = Ponsse Elk with Fomatec tracks, [3] EFw = Ponsse Elk with Fomatec tracks equipped with add-on track shoes, [4] Kopa = Ponsse Buffalo with KOPA high flotation tracks, [5] E10W = Ponsse Elk 10 W with Olofsfors mixed tracks, [6] Average of fixed and add-on track shoes, [7] Nominal Ground Pressure NGP_{adj} = NGP/(track shoe coverage/100)

NGP_{adj} are considerable, e.g. the EFwo rear NGP_{adj} is roughly 2.9 times that of Kopa.

The studied tracks are displayed in Figure 1. Olofsfors Baltic (Figure 1a front) and Olofsfors Magnum (Figure 1a rear) are widely used flotation tracks with fairly high track shoe coverage. Fomatec Rud Combino Hybrid is a new type of track, which in the basic form (Figure 1b) is an open universal year-round track, but can be transformed into a flotation track with a fairly high track shoe coverage by bolting on additional shoes (Figure 1c). The track shoe coverage of Fomatec tracks was reduced by the need for several long track locks, two of which can be seen on top of the front bogie wheels. The manufacturer was in the process of changing the design so that these sections will be more effectively covered by track shoes in the future. Kopa Flotation (Figure 1d) is a flotation track with excavator-type track shoes and extremely high track shoe coverage. Olofsfors Evo Soft (Figure 1e front) is a universal year-round track with average track shoe coverage, and Olofsfors Max-Magnum (Figure 1a rear) is a mixed-type track with average track shoe coverage, with emphasis placed on both traction and flotation properties.

Measurement of study conditions

Soil conditions were assessed along the center line of the test trails prior to harvesting. Peat depth was determined with a steel rod. The groundwater table level was measured using inserted plastic perforated tubes, sampling with an electric cable which detects the water surface on contact. Shear modulus was chosen to describe soil strength, and was determined with a spiked shear vane (Ala-Ilomäki 2013, Figure 2) at 1.5 m and 3.5 m on each 5 m long study plot on the straight test trails and at 2 m intervals on the curved trails. Peat moisture was determined from three peat samples taken in the beginning, the middle and the end of each test trail with a box-type, 60 mm by 60 mm peat sampler (Pitkänen et al. 2011). A 100 mm section from the top of the composed peat layer beneath the living moss layer was used for moisture determination. The samples were weighed fresh, oven dried at 105°C for three days until there was no further change of the sample mass, and weighed again dry. To measure shear modulus, the head of the spiked shear vane was hit in vertical direction into the peatland so that the spike attachment plate was flush with the peatland surface. When the spikes penetrated into the root mat, the vane was rotated manually 5° to 15° while measuring the rotation angle and torque with an electronic torque wrench. Shear modulus was then calculated as described by Ala-Ilomäki (2013).

The trees located on the trails were surveyed prior to cutting on 8 m wide and 5 m long plots on the straight trails and on an 8 m wide zone on the curved trails. Tree species, diameter at breast height (DBH) and the height of every third tree were

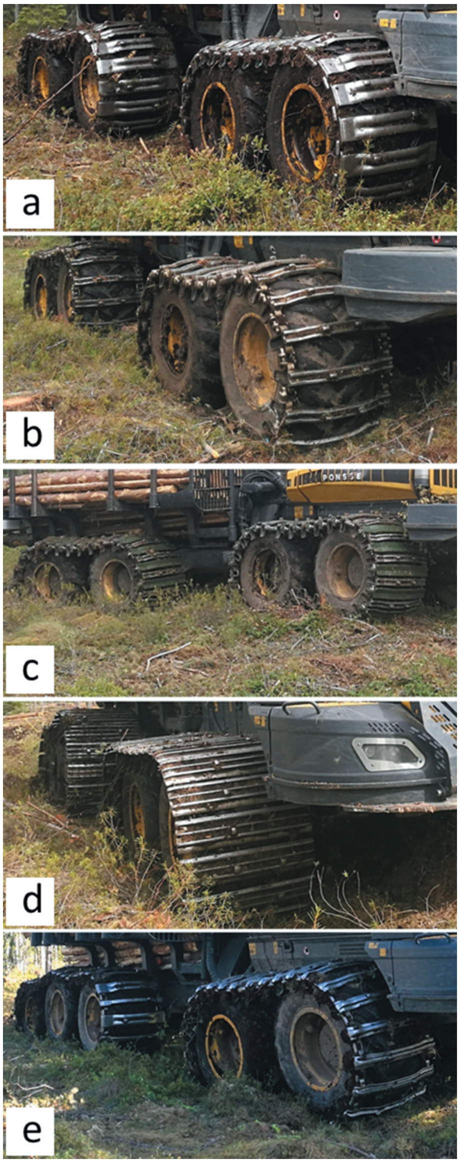

Figure 1. The five bogie track sets studied: a) Olofsfors Baltic (front) and Olofsfors Magnum (rear) b) Fomatec Rud Combino Hybrid without add-on track shoes c) Fomatec Rud Combino Hybrid with add-on track shoes d) Kopa Flotation e) Olofsfors Evo Soft (front) and Olofsfors Max-Magnum (rear).

determined, combining field records and laser-based height meter Nikon Laser Forestry Pro II.

Data analysis

To analyze rut formation, a model incorporating all measured variables was proposed. To be included, the variables had to be significant at the 0.05 level. It was expected that each machine presented a different rut formation, resulting in a hierarchical structure of the data with individual observations grouped by machine and plot. Therefore, the data was analyzed using a mixed model approach, following (Equation 1):

$$R_{ij} = \beta_0 + \beta_1 \times logG_{ij} + \beta_2 pass_{ij}\{1-4\} + \mu_i + \varepsilon_{ij} \qquad (1)$$

Figure 2. The spiked shear vane used for measuring shear modulus. The length of the spikes is 170 mm and outer diameter of the array is 200 mm.

where R_{ij} is average rut depth (cm) of machine i in plot j, G_{ij} is shear modulus (kPa) measured in the plot j operated by machine i, $pass_{ij}$ is dummy variable representing the number of passes of machine i in plot j, being = 1 for the measurements of that machine at that pass, and 0 otherwise, for a total of four passes. Random factors μ_i and ε_{ij} correspond to the between-machine variability and residual variability, respectively, following a normal distribution with mean = 0 and standard deviations σ_m and σ_ε, respectively. Finally, coefficients β_x represent parameters to be estimated. Initially, a variable representing the type of trail (curve or straight) was considered but did not prove significant.

Results

Stand and soil properties

The variation of stand properties between the test trails was considerable (Table 2), which was to be expected from a peatland stand of natural origin. The stand on the curved trail of E10Wstands out for its low basal area and highest stand density among the trails. The variation in soil properties, with the exception of peat moisture content, was high. The average shear modulus in the straight trail of LWB was roughly four times the average in the rest of the trails.

Rut formation

The average rut depth was 15.47 cm (std. dev = 7.59 cm), with some extreme values close to 40 cm and around 0 cm (Figure 3). In some cases (N = 4), negative rut depth was

Table 2. Stand and soil properties on the test trails. For machine abbreviations see Table 1 footnote.

	Studied machine and test trail									
	LWB		EFwo		EFw		Kopa		E10W	
Stand or soil property	Straight	Curved	Straight	Curved	Straight	Curved	Straight	Curved	Straight	Curved
Average DBH, cm	12.3	14.5	16.3	14.9	16.2	16.4	15.8	15.7	15.5	7.0
Average height, m	11.6	13.5	14.0	13.4	14.0	15.0	13.8	13.6	14.2	7.2
Basal area, m^2ha^{-1}	26.5	26.2	28.9	20.9	23.3	25.1	27.8	24.3	19.3	16.0
Stand density, stems/ha	1813	1394	1125	1036	938	1116	1188	1076	938	2311
Volume, m^3ha^{-1}	199.9	204.1	245.8	161.2	188.8	197.4	227.5	192.7	145.6	112.4
Volumetric share, %	96.8	98.0	97.1	98.4	99.4	99.8	99.5	96.7	99.6	95.2
Scots pine *(Pinus sylvestris)*	2.7	1.4	2.9	1.4	0.0	0.2	0.4	3.1	0.0	1.1
Norway spruce *(Picea abies)*	0.5	0.6	0.0	0.2	0.6	0.0	0.1	0.2	0.4	3.8
Silver birch *(Betula pendula)*										
Average peat depth, cm	124	129	138	152	108	164	162	161	159	229
Average ground water depth, cm	22	15	26	32	35	37	33	30	34	23
Average peat moisture, %	85.0	86.9	85.9	86.2	85.7	88.9	84.7	86.5	87.1	89.7
Average peatland surface shear modulus, kPa	205	51	71	64	56	44	52	44	48	56
Range of peatland surface shear modulus, kPa	91 … 383	38 … 68	40 … 94	30 … 138	46 … 68	24 … 95	36 … 73	24 … 57	35 … 68	26 … 93

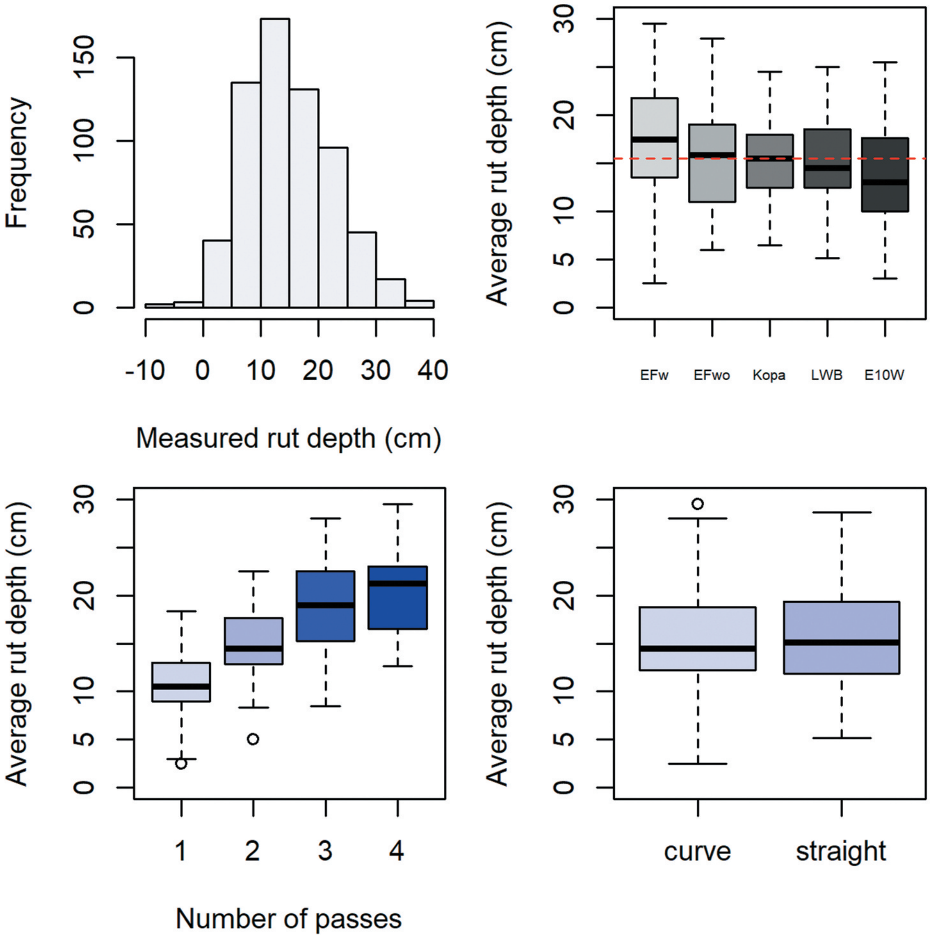

Figure 3. Descriptive statistics of the variables: distribution of the measurements of rut depth and average values by machine, number of passes and type of trail. The boxes represent the values between the 1^{st} and the 3^{rd} quartiles, whereas the bars correspond to 95% of the measurements (line inside the box represents the median value). For machine abbreviations see Table 1 footnote.

measured, due to the measurement point being located adjacent to a stump where consistency in measurement along the passes was challenging. The initial analysis showed an increment of rut depth with number of passes, and some noticeable differences between the machines. There were no evident differences between the curve and straight trails.

The analysis using a combined model (Equation 1) showed a strong significance of the increasing number of passes on the

Table 3. Rut formation model parameters (Equation 1) for the studied machines, test trails and estimated realizations for each machine analyzed (R^2 = 0.55, $\sigma_{machine}$ = 1.40, corresponding to between-machine variability). SE: Standard error. For machine abbreviations see Table 1 footnote.

Variable	Value	SE	t-value	p-value
β_0	20.541	2.360	8.705	<0.001
β_1 (log G)	−5.532	1.283	−4.312	<0.002
β_2 pass2	4.094	0.693	5.911	<0.003
β_3 pass3	7.652	0.693	11.047	<0.004
β_4 pass4	10.311	0.969	10.642	<0.005
μ (Kopa)	0.285			
μ (E10W)	0.425			
μ (Efw)	0.450			
μ (Efwo)	−2.192			
μ (LWB)	1.032			

rut depth (Table 3), and an inverse correlation with the shear modulus (G). For EFw, EFwo and LWB, the observed average rut depth on curves (17.4 cm, 14 cm and 16.16 cm, respectively) was higher than in the straight segments (13.1 cm, 13.12 cm and 13.56 cm, respectively). In the rest of the cases, it was lower in curves (15 cm and 15.6 cm versus 16.6 cm and 19.9 cm for Kopa and E10W, respectively). In the case of E10W and EFw this difference was significant (p-values <0.001 and <0.01, respectively, for −4.3 cm and +4.3 cm deviations of the mean in curves) when analyzed independently (*anova*, considering *pass* and *curve* as dummies, one model per machine). However, when combined with the rest of the variables in a single model, the type of trail (*curve* or *straight*) did not show a statistical significance (p-value = 0.230), and was excluded from the final version. Alternative models with interactions between these variables were also tested but did not show significance. The fixed part of the model produced a good fit (R^2 = 0.48), which was improved (R^2 = 0.55) by including the between-machine effects. The variability due to the different machines was relevant (std. dev = 1.40 cm versus residual std. dev = 3.63 cm). The overall RMSE of the fixed part was 3.81 cm (24.5%), and the bias was −0.1 cm (<0.7%). No obvious relationships nor patterns indicating a systematic trend among the residuals and the independent variables were observed, thus suggesting unbiased predictions.

The predictions using the model illustrated the differences between the machines tested (Figure 4). Following the model predictions, three groups could be identified: 1. EFwo, which showed the lowest rut formation, followed by 2. EFw, Kopa and E10W, which showed nearly equal rut formation, and 3. LWB, which showed the strongest rut formation. In Figure 4 the shear modulus range of the test trails for the tested machines is displayed, demonstrating that the range for LWB was clearly the widest.

Discussion

The study conditions were quite typical for Finnish drained peatlands. Estimating soil strength before the experiment was challenging, a characteristic of this site type. The results indicate that the spiked shear vane measuring provided reasonable shear modulus measurements, which described soil strength well.

The forwarders in the trial were not identical and their net mass without tracks varied from 17,950 kg to 20,700 kg. Differences in forwarder design and track equipment resulted in estimated gross vehicle mass varying between 27,450 kg to 31,600 kg, the range being 4,150 kg or roughly 13 % of the average gross vehicle mass. Considering model results for Fomatec tracks with and without add-on track shoes mounted on the same forwarder, the add-on track shoes corresponding to a 2,000 kg mass difference may have had a remarkable effect on rut formation under the study conditions. When comparing track designs, it would be ideal to have identical vehicles with the same mass and same track width. Here, different vehicle designs were involved, so differences in mass, weight distribution and vehicle dynamics were inevitable.

The 5,100 kg load mass was low from a practical point of view. It was chosen based on operator judgment taking into account the prevailing conditions. Soon it was obvious that a bigger load would have been feasible, but it was necessary to maintain equal load for all forwarder and track configurations. Further, the conditions on the peatland did not allow for any extra test trails to be laid out. However, doubling the load would have resulted in a load more typical for practical operations. This would have increased the mass of the rear frame by roughly a third and caused the rear frame to be clearly heavier than the front one for all studied machines. Heavier loading could have affected the rut formation of tracks, especially in case of low track shoe coverage.

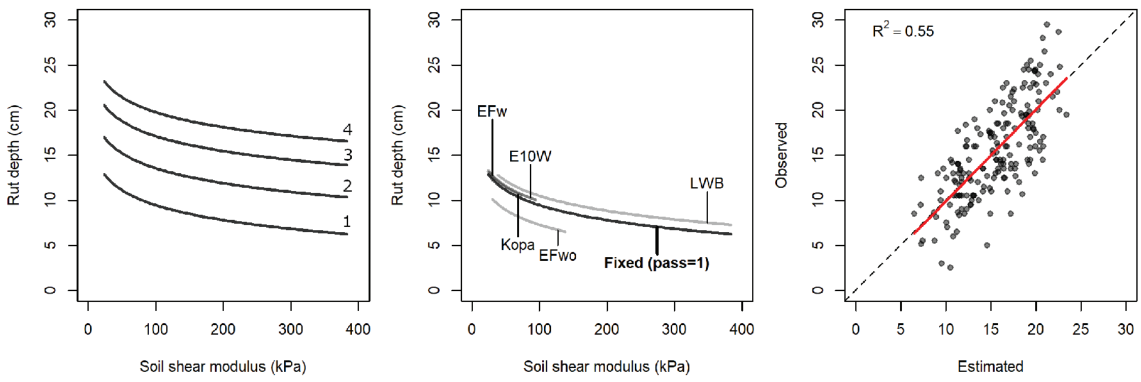

Figure 4. Modeled relations between rut depth (cm) and the soil's shear modulus (kPa) according to number of passes and machine. Up: Average effect by number of passes 1 to 4. Bottom: Average effect of each machine, for the first pass. In this case, the lines include the ranges in the measured shear modulus. The central line is the average effect. Right: model performance. The estimated between-machine standard deviation was 1.40, and the residual standard deviation was 3.60. For machine abbreviations see Table 1 footnote.

The combined effects of the different variables, the different ranges of peatland surface shear moduli by the machines, and the possible specific effects of the machines justified the modeling approach, making it possible to address the complex interactions between the variables studied. The effects concerning soil shear modulus and number of passes were consistent and similar, independently of the machine analyzed. However, the modeled rut formation of EFwo, despite the lowest track shoe coverage, was the lowest among the studied machines, which may be explained by the lowest gross vehicle mass. Contrarily, track shoe coverage and, accordingly, NGP_{adj} did not play a key role in rut formation under the study conditions. On weaker soil, this might change if NGP_{adj} would be sufficiently high to puncture or shear through the peatland surface layer. NGP_{adj} of EFwo was close to puncturing or shearing pressures measured by Ala-Ilomäki (2005) in plate loading tests on peatland with 0.10 m and 0.15 m diameter plates.

Despite the low stand volume, the shear modulus in the curved trail of E10W was not exceptionally low, which may indicate the reinforcing effect of the root system of small trees and other plants, such as shrubs. The lower modeled rut formation of E10W compared to LWB is logical considering the longer rear bogie wheelbase. The positive effect of longer rear bogie wheelbase of LWB compared to a standard rear bogie could not be confirmed, as a similar machine with standard rear bogie wheelbase was not included in the field test. Rut depth showed opposite signs in curve versus straight trail segments when analyzed individually by each machine. This indicates that the lateral shearing and soil displacement action of bogie tracks in curves was the decisive factor in rut formation under the study conditions. The sharp angular form of EFwo and EFw track shoe ends is likely to shear soil in curves. The 20 m radius of curvature was fairly wide, and there was very little difference in the level of rut formation between straight and curved trails. In this, the present study differed from a study by Gelin and Björheden (2020), where the curved trail had smaller turning radii, oscillating steering angle (S-bend) and 8 to 10 passes. In addition, the load size in the study by Gelin and Björheden (2020) was roughly double the load in the present study. Both more challenging test trail conditions and a heavier load mass are likely to cause more soil shearing.

NGP or NGP_{adj} for track shoe coverage did not explain the differences in rut formation. The soil strength on the test trails was sufficient to support the loading exerted by the studied forwarders for three to four passes. The peatland surface was thus not punctured by the track shoes, but sheared at the track edges on the sides, where the radius of curvature of deformed peatland surface is the smallest. Previous experience of the authors support this observation. Therefore, track shoe coverage was not critical in the prevailing conditions. Increasing track shoe coverage will lead to increasing track mass and increased loading to be supported by the soil.

Conclusions

In conclusion, despite the differences observed, all track and forwarder designs performed with satisfactory results in terms of vehicle mobility. Therefore, the choice of track or forwarder under the given test conditions was not critical, as none of them performed vastly inferior in comparison to the others. From a soil and stand conservation point of view, the difference in the rut formation of the studied machines is to be taken into consideration. On soils with a lower strength, the importance of track shoe coverage may increase. Vehicle dynamics on peatlands are still far from being fully understood; accordingly, there is considerable potential for future research. This could be done most conveniently in computer simulation, where track design and weight distribution could easily be altered, while keeping vehicle mass constant.

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