

Article

Potential for Expanding Summertime Timber Harvesting on Drained Peatlands Under Operational Stand Conditions: A Site-Specific Case Study

Oiva Hiltunen ¹, Ville Hallikainen ²  and Teijo Palander ^{1,*} 

¹ Faculty of Science, Forestry and Technology, University of Eastern Finland, P.O. Box 111, 80101 Joensuu, Finland; oiva.hiltunen@gmail.com

² Natural Resources Institute Finland, Ounasjoentie 6, 96300 Rovaniemi, Finland; ext.ville.hallikainen@luke.fi

* Correspondence: teijo.s.palander@uef.fi

Abstract

The expansion of sustainable timber harvesting on peatland forests is important for forest owners, contractors, and the forest industry. This study investigated the effects of site-specific conditions on summertime harvesting operations and modeled the influence of a light nine-ton forwarder on rut formation. Three logistic mixed-effects models predicted peat surface disturbance (ROC = 0.60, 0.63, and 0.67), while a linear mixed model predicted rut depth when rutting occurred ($R^2 = 0.35$). Rut formation was associated with the number of machine passes, cumulative load, groundwater table depth, peat layer thickness, and interactions between stand and harvesting variables. The results indicate that timber can be successfully forwarded from drained peatlands with limited bearing capacity when operations are adapted to local site conditions. The findings highlight the importance of road-network planning, load management, and operator decision-making in reducing rut formation. This modeling approach also supports operator training, thereby contributing to more sustainable timber harvesting on low-bearing-capacity sites.

Keywords: environmental sustainability; forwarder; planning; road network; rut formation; tacit knowledge

1. Introduction

Climate change is expected to shorten the winter season in northern coniferous forests, including southern Lapland, by about one month by 2050 [1]. Winter logging is generally considered advantageous because frozen soil and snow cover increase the bearing capacity of peatlands. Consequently, the period suitable for winter timber harvesting is shrinking, increasing the importance of harvesting on peatlands with low bearing capacity and seasonally fluctuating groundwater levels.

Current forest management trends in Europe emphasize environmental sustainability and climate-resilient continuous cover forestry supported by advanced harvest planning tools [2–5]. In peatlands, this has led to less intensive drainage practices, as maintaining forest cover and higher groundwater levels can reduce greenhouse gas emissions from peat decomposition [6]. During the growing season, a groundwater depth of 30–40 cm is generally sufficient for tree growth [7,8], and this can often be achieved with relatively shallow ditches, depending on site conditions [9].

Soil moisture strongly affects load-bearing capacity and rut formation in peatlands [10,11]. Shallower ditches and reduced ditch network maintenance raise ground-



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water levels and increase soil moisture, thereby decreasing bearing capacity. This trend is evident in southern Lapland, where ditch network maintenance has declined markedly since the early 2000s [12]. Because tree-mediated groundwater regulation and evapotranspiration are lower in northern than in southern Finland [8], maintaining critical ditch networks remains important for water management and trafficability [7,13–16].

Timber harvesting on peatlands is gaining importance in Finland because of increasing wood demand and reduced imports [17]. In southern Lapland, drained peatlands are expected to provide about 25% of all harvested timber within the next decade, highlighting the need for effective summertime harvesting methods [12]. For planning purposes, sustainable timber harvesting operations are governed by standards for rut depth, tree damage, strip road spacing and width, thinning intensity, and tree selection [18].

The decades-long trend towards heavier forwarders may not support sustainable summer harvesting on drained peatlands. The operating weight of forwarders has increased from 10–13 tons in the 1980s to approximately 18–19 tons today, resulting in a fully loaded machine mass of 35–40 tons. Although track equipment can improve load-bearing performance [19,20], development has largely focused on adapting machinery designed for mineral soils to peatland conditions [21].

The load-bearing capacity classification was developed for southern Finland to support the planning of timber harvesting on peatlands [22]. The load-bearing capacity classification defines the site conditions under which a forest machine with specific equipment can operate on peatlands outside the ground-frost period. The classification considers the initial volume of a stand per hectare before harvesting, the type of harvesting machinery, the average forest haulage distance, the groundwater level, the rainfall over the previous four weeks, peat layer thickness, and the road network at the harvesting site. In addition to these conditions, the distribution of logging residues on forwarding trails can substantially improve bearing capacity and reduce rut formation during forwarding operations [23–25].

Forest road network planning affects timber harvesting costs [26]. Although spatial data and decision-support systems are increasingly available [27], successful timber harvesting on low-bearing-capacity peatlands still depends heavily on operators' experience in adjusting routes, load sizes and harvesting sequences to local conditions [28]. Apart from terrain slope and carrying capacity, which are known to influence route selection, the factors affecting road network planning remain poorly understood. Inadequate planning may lead to soil disturbance, compaction, and rut formation, thereby damaging forest soils [29]. In peatlands, rutting is the most significant form of damage because it affects shallow root systems and can reduce tree growth for up to ten years after harvesting [30,31]. Although wider road networks may reduce rutting by allowing alternative machine routes [32], they can also increase growth losses [31].

Recent EU biodiversity, soil, and forestry initiatives are expected to affect future timber harvesting practices and costs [33]. Together with national forest management recommendations, these policies increase the need for precise harvest planning on peatlands to minimize environmental damage [34], particularly as forest machinery continues to become heavier. A potential drawback of lighter forwarders is that they require a greater number of trips, which may increase the risk of rut formation. Rutting is influenced not only by machine traffic but also by site conditions, harvesting practices, road layout, and load management [21]. However, the relative importance of site conditions, harvesting practices, road layout, and machine loading in explaining rut formation remains insufficiently understood, particularly under operational harvesting conditions where most rutting occurs during the first machine passes. This study addresses this knowledge gap by modeling rut formation on drained peatlands.

The aim of this study was to determine whether summertime timber harvesting can be expanded on drained peatlands with lighter machinery, preplanning, and operator decisions without unacceptable rutting.

The objectives of this paper were

- to measure rut formation and timber harvesting under normal operational practice,
- to model the main factors affecting rut development,
- to model the trafficability under an increasing number of passes and cumulative total load (tons),
- to provide recommendations for operational planning and decision-making.

2. Materials and Methods

The study site (5.8 ha) was a typical drained peatland with ditch spacing ranging from 37 to 49 m and was harvested by thinning during the summer (Figure 1). Ditch condition was classified as below average or poor according to [35], representing a common condition in drained peatlands with limited maintenance drainage.

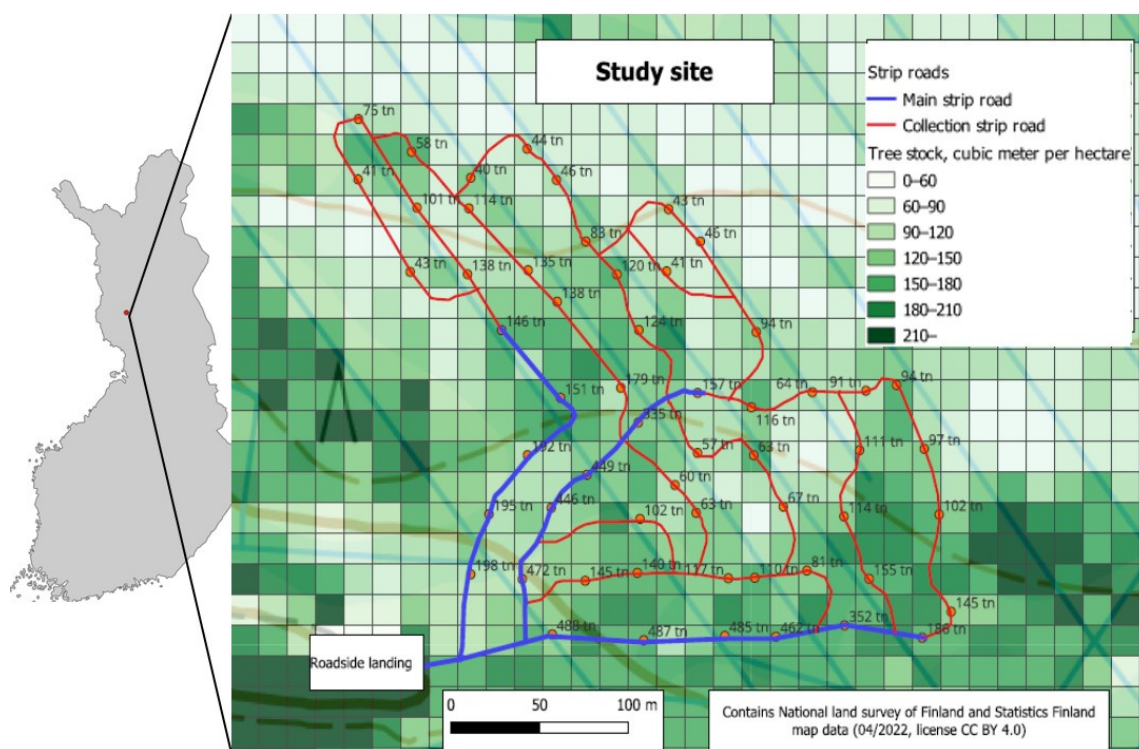


Figure 1. The basic map displaying the ditch network (ETRS-TM35FIN 7368023,425587). Area-based laser scanning stand volume data with a resolution of 16×16 m is overlaid on the map, with sample plots marked in red along with the road network. The cumulative total load (in tons) is indicated at the location of each sample plot.

The peat thickness on the plot was determined as an average based on five measurement points. In the center of the sample plots, excavation was used to measure the water table level. Groundwater table measurements for the sample plots were recorded either on the day of timber forwarding or on the preceding day, depending on the progress of the forwarding operation. For sample plots located on main forwarding roads, machine traffic occasionally occurred over multiple days; therefore, the measured groundwater table level did not always coincide with the timing of every forwarding pass. However, the entire timber forwarding operation was completed within 76 h. Stand volumes were measured on these plots, which were divided into three categories: $75\text{--}120 \text{ m}^3\text{ha}^{-1}$ (V120, $n = 23$),

120–150 m³ha^{−1} (V150, n = 21), and 150–181 m³ha^{−1} (V180, n = 13). This classification was carried out, in principle, as outlined in [22], considering, however, that the average stand volume (m³ha^{−1}) is significantly lower in northern Finland.

The road network was planned after the sample plots had been established so that the forest haulage (forwarding) distance would be as short as possible considering prevailing site and stand characteristics. Due to the experimental design, road spacing was approximately 32 m, leaving some unthinned space between the roads. The standard strip road spacing in thinning operations was not used, which is approximately 20 m, which is primarily determined by the crane reach of the harvesting machinery. The roads went straight through the center of the plot. The objective was to position the main roads in areas where the stand volume mainly represented groups V150 and V180, although some parts of the main roads passed through area belonging to group V120. The network design of all roads was aimed at keeping the number of passes on the collection road between 2 and 5. The selection of strip-road locations was informed in part by previous studies of peatland bearing capacity [20,22,24]. The average forest haulage distance was 310 m, of which approximately 260 m was on drained peatland.

2.1. Implementation of Timber Harvesting

Timber harvesting was carried out from 11 August to 17 August 2017, using a six-wheeled Komatsu 901TX harvester (Komatsu Forest AB, Umeå, Sweden). The machine was equipped with Clark TXL 24 mm tracks (Clark Tracks, Loimaa, Finland) and front chains. The track shoe width was 930 mm. The total operating weight of the harvester, including equipment, was 20.4 tons, and the nominal ground pressure (NGP, 8%) was 43 kPa. The average harvesting removal was 66 m³ha^{−1}.

Forwarding was carried out from 17 August to 20 August 2017, using an eight-wheeled John Deere 810E forwarder (Deere & Company, Moline, IL, USA) with a payload capacity of 9 tons. The forwarder was equipped with Clark TXCL 24 mm tracks (Clark Tracks, Loimaa, Finland) on the front wheels and Clark TXL 24 mm tracks on the rear wheels, both with a track shoe width of 930 mm. The total operating weight of the forwarder, including equipment, was 17.1 tons.

The mean load weight was 9.7 tons for coniferous timber and 6.2 tons for birch pulpwood, with corresponding mean log lengths of 402 cm and 302 cm, respectively. Depending on the load weight during loading (1.1–10.3 tons), the nominal ground pressure (NGP, 8%) exerted by the forwarder varied between 28 and 43 kPa among the sample plots.

During the forwarding period, total rainfall amounted to 17.9 mm, corresponding to an average of 4.5 mm day^{−1}. For comparison, the mean daily rainfall in August 2017 was 1.7 mm day^{−1}. Groundwater table measurements for the sample plots were recorded either on the day of timber forwarding or on the preceding day, depending on the progress of the forwarding operation. For sample plots located on main roads, machine traffic occasionally occurred on multiple days, and therefore, the measured groundwater table level did not always coincide with the timing of all forwarding passes. The entire timber forwarding operation was completed within a period of 76 h.

In the forwarding analysis, the cumulative machine load (tons per sample plot) was used as the classification criterion. The cumulative machine load was calculated as the sum of the harvester weight and the forwarder weight, including timber loads, for all machine passes within a sample plot. Based on the cumulative machine load after all passes, the plots were classified into three categories:

- Class 100: cumulative machine load < 100 tons (n = 22);
- Class 200: cumulative machine load ≥ 100 tons and <200 tons (n = 26);
- Class 400: cumulative machine load ≥ 200 tons (n = 9).

The machine operator had more than 15 years of experience in both harvesting and forwarding operations. A harvesting plan was provided to the operator before the operation. During harvesting, the operator assessed site conditions and subsequently determined the forwarding routes, driving sequence, and load sizes. This requires the operator to adapt harvesting operations to site conditions in a sustainable manner.

Harvesting was conducted first throughout the entire study area, after which the timber was forwarded to the roadside landing. Based on observations made during harvesting, the operator identified areas where the load-bearing capacity of the peatland was likely to restrict the size of forwarding loads or the number of machine passes.

2.2. Timber Harvesting Measurements

Prior to harvesting, stand volume, tree height, and crown base height were measured in each sample plot. Tree-species-specific stand volumes were calculated using height curves and volume equations [36]. After harvesting, stand volume was remeasured [36], and the harvested volume was calculated as the difference between the pre-harvest and post-harvest stand volumes. In addition, all harvested timber was measured using the forwarder's onboard weighing system.

The amount of crown biomass was estimated separately for each tree species using the biomass models developed in [37,38], based on the dry mass of living and dead branches. Biomass values (kg) were converted to solid wood volume using the logging-residue chip density values reported in [39], including needles: 395 kg m^{-3} for Scots pine, 425 kg m^{-3} for Norway spruce, and 500 kg m^{-3} for birch. The volume of stem wood remaining in treetops was estimated using the volume tables in [36]. The minimum top diameter was assumed to be 6 cm for conifers and 7 cm for birch. Small trees ($\text{DBH} \leq 8 \text{ cm}$) were classified as crown biomass. Thus, crown biomass included branches, foliage, and stem biomass not recovered during harvesting. The amount of crown biomass removed from each plot ($\text{dm}^3 \text{ m}^{-2}$) was calculated as the difference between the estimated crown biomass of the pre-harvest stand and that of the residual stand after harvesting.

For each forwarder load, travel routes and distances were recorded separately for loaded and unloaded travel, and harvester routes were documented during harvesting. These data were used to determine the number of harvester and forwarder passes within each sample plot, as well as the load associated with each pass and the cumulative machine load.

Forwarding trail width was measured according to the inspection guidelines of the Finnish Forest Center [40]. Rut-length measurements deviated from the guideline, which records only one rut when both wheel tracks are rutted at the same location. In this study, both wheel-track ruts were measured, resulting in greater reported rut lengths than would be obtained using the standard procedure.

The ruts were formed within the sample plots during both loaded and unloaded forwarding. After each forwarder pass, the length and depth of all ruts within the sample plot were measured, including any newly formed ruts. Rut depth was recorded at the deepest point of each rut [38]. The mean rut depth for each sample plot after each pass was calculated as a rut-length-weighted average.

2.3. Modeling Rut Formation and Rut Depth

Prior to correlation analysis and model fitting, correlation analysis and differences in timber harvesting variables among the three cumulative machine-load classes were evaluated using the Kruskal–Wallis (K–W) test based on measurements from the final forwarding pass ($n = 57$). Because the data did not meet the assumptions of parametric

tests and group sizes were unequal, pairwise comparisons between main trails ($n = 16$) and secondary trails ($n = 41$) were performed using the Mann–Whitney U (M–W) test [41].

Rutting was analyzed using a two-part (hurdle-type) modeling approach. In the first stage, rut formation was treated as a binary response variable. A plot was classified as unrutted when the peat surface remained intact and rut depth could not be measured (0); plots exhibiting rutting were coded as 1. The probability of rut formation was analyzed using logistic mixed-effects models. In the second stage, only observations with measurable rutting (rut depth > 0 cm) were included, and rut depth was analyzed using linear mixed-effects models.

The logistic models were fitted using the glmmPQL function in the MASS package [42], allowing the inclusion of a first-order autoregressive [AR(1)] correlation structure. Model predictions were generated and visualized using the effects package [43,44], and model discrimination was evaluated using the area under the receiver operating characteristic (ROC) curve calculated with the pROC package [45].

Rut depth was analyzed using the lme function in the nlme package [46]. Fixed-effect predictions and 95% confidence intervals were generated using the effects package, and the coefficient of determination (R^2) was calculated using the performance package [47]. All analyses were conducted in R [48]. The structure of the logistic autoregressive mixed-effects model (Models 1 and 2) fitted to the longitudinal dataset can be expressed as follows:

$$y_{ij} \sim \text{binomial}(n_{ij}, \pi_{ij}) \quad (1)$$

$$\text{logit}(\pi_{ij}) = \ln\left(\frac{\pi_{ij}}{1 - \pi_{ij}}\right) = f(X_{ij}, \beta) + \mu_i \quad (2)$$

where y_{ij} denotes the observed binary response for sample plot i at measurement occasion j , and π_{ij} is the probability of rut formation. The term $\ln\left(\frac{\pi_{ij}}{1 - \pi_{ij}}\right)$ represents the logit link function. The function $f(\cdot)$ represents a linear combination of the fixed predictors X_{ij} , and β denotes the corresponding fixed-effect parameters. The term μ_i represents the normally distributed random effect of sample plot i . The repeated measurements within sample plots were assumed to follow a first-order autoregressive [AR(1)] correlation structure, characterized by the autocorrelation parameter ϕ . Thus, observations at times t and $t - 1$ were assumed to be correlated, with measurements closer in time exhibiting stronger correlations than those further apart.

A linear mixed-effects model (Gaussian distribution; Model 3) was used to analyze rut depths > 0 cm. Rut depth was log-transformed to improve normality. The model included a random sample plot effect and repeated measurements within plots:

$$\ln(y_{ij}) = f(X_{ij}, \beta) + \mu_i + \varepsilon_{ij} \quad (3)$$

Here, y_{ij} is the rut depth in sample plot i at measurement occasion j , β represents fixed effects, μ_i the random plot effect, and ε_{ij} the residual error. Residuals were assumed to follow an AR(1) correlation structure to account for temporal dependence among repeated measurements.

3. Results

Rutting occurred in 39 of the 57 sample plots and was more frequent during loaded than unloaded passes (Table 1). The number of rut formation events averaged two per plot, ranging from one to seven. Thirteen plots belonged to the 100-ton load class (mean cumulative load 71 t), 17 to the 200-ton class (143 t), and nine to the 400-ton class (442 t).

Table 1. Rut formation observed during timber harvesting machine passes. Rut status was classified as unchanged (A), increased (B), or decreased (C) during unloaded (U) and loaded (L) machine passes. Values represent the total number of observations and the number of sample plots.

Observations	Mean	Minimum	Maximum	Total	Plots
AU	4.7	1	14	169	36
AL	2.9	1	8	57	20
BU	1.2	1	2	16	13
BL	2	1	5	74	37
CU	1.4	1	3	10	7
CL	1.5	1	3	24	16

Eighteen sample plots remained free of rutting, almost all of which were located on collecting roads. On average, each plot was traversed five times: three times by an unloaded machine and twice by a loaded forwarder. Nine plots belonged to the 100-ton load class, with an average cumulative load of 52 t, and nine plots belonged to the 200-ton load class, with an average cumulative load of 134 t. Across all rut-free plots, the mean cumulative load was 93 t, ranging from 40 to 186 t.

Site variables did not differ between plots with and without rutting. However, total cumulative load ($p = 0.014$), total number of passes ($p = 0.018$), and number of loaded passes ($p = 0.006$) were significantly higher in plots where rutting occurred.

3.1. Analysis of Rut Formation

Deep ruts (>20 cm) represented only 5.3% of the trail length. Both average rut depth and rut length increased with cumulative load, and rut length approximately doubled between the 200-ton and 400-ton load classes (Table 2). However, road width, maximum rut depth, and the length of deep ruts (>20 cm) did not differ significantly among load classes (K–W, $p > 0.05$). In contrast, the number of ruts differed significantly between load classes (K–W, $p = 0.011$), whereas differences in total rut length were marginally non-significant (K–W, $p = 0.11$). All sample plots in the 400-ton load class were located on main roads, while most plots in the 100-ton load class were located on collecting roads.

Table 2. Rutting characteristics across cumulative load classes. N = number of sample plots; A = number of passes; B = road width; C = number of ruts; D = maximum rut depth; E = total rut length; F = rut length with a depth > 20 cm; G = cumulative load. Values are arithmetic means, except for maximum rut depth, which is a rut-length-weighted mean.

Load Class t	N n	A n	B m	C n	D cm	E m	F m	G t
100	22	3.1	5.5	1.1	10.3	2.7	1.4	63
200	26	6.7	5.1	1.6	11.6	3.3	1.9	140
400	9	21.3	5.2	3.2	18.0	6.5	3.0	442
All	57	7.6	5.2	1.7	12.2	3.6	1.9	158

3.2. Analysis of Stand and Timber Harvesting Variables

Figure 2 shows that load classes differed primarily in traffic intensity and average load weight, while groundwater level, harvesting removal, and crown biomass remained similar across classes.

Compared with main-road plots, collecting-road plots had thicker peat layers, shallower groundwater tables, lower stand volumes, and higher pine crown mass (Table 3). In contrast, spruce crown mass was greater along main roads. Despite substantial differences

in traffic intensity and cumulative load, the length of deep rutting (>20 cm) did not differ significantly between road types.

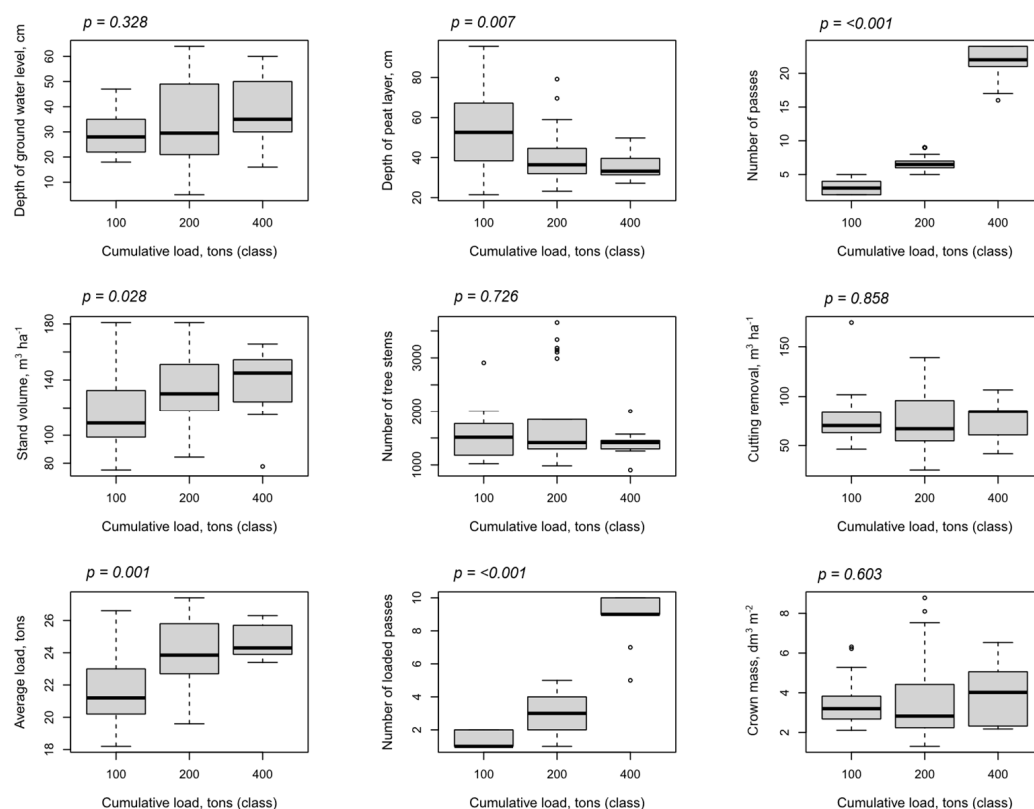


Figure 2. Stand and timber harvesting variables across the 100-ton (Class 1), 200-ton (Class 2), and 400-ton (Class 3) cumulative load classes. Differences among classes were tested using the Kruskal–Wallis test.

Table 3. Comparison of stand and timber harvesting variables between main-road (A) and collecting-road (B) plots using the Mann–Whitney U test. Values are arithmetic means.

Variables	Unit	A	B	p-Value
Thickness of peat layer	cm	33.8	49.2	<0.001 ***
Depth of ground water table	cm	38.1	30.8	0.066
Number of ruts	n	2.6	1.3	0.006 **
Total length of the rut	m	5.3	2.9	0.009 **
The rut length when rut depth > 20	cm	2.4	1.7	0.094
Number of passes	n	15.6	4.5	<0.001 ***
Number of loaded passes	n	6.7	2.1	<0.001 ***
Cumulative load	t	325	93	<0.001 ***
Average load	t	25	22.5	<0.001 ***
Stand volume	$\text{m}^3 \text{ha}^{-1}$	140	122	0.022 *
Removal of timber harvesting	$\text{m}^3 \text{ha}^{-1}$	69.7	67.8	0.790
Crown mass	$\text{dm}^3 \text{m}^{-2}$	3.7	3.8	0.382
• Crown mass of pine	$\text{dm}^3 \text{m}^{-2}$	0.96	1.74	0.012 *
• Crown mass of spruce	$\text{dm}^3 \text{m}^{-2}$	1.38	0.80	0.034 *
• Crown mass of birch	$\text{dm}^3 \text{m}^{-2}$	1.33	1.21	0.569

*, **, *** = statistical significance is <0.05, <0.01 or <0.001, respectively.

3.3. Modeling

The probability of peat surface disturbance increased with both the number of forwarder passes and cumulative load (Models 1 and 2; Table 4). In addition, groundwater depth was a significant stand predictor of disturbance probability in Model 3. It signif-

icantly modified the effect of traffic intensity, whereas stand volume and stem density became significant only through their interactions with the number of passes (Table 4). Disturbance probability increased markedly with increasing traffic intensity, particularly at lower groundwater depths and higher stand volumes. Under these conditions, peat surface disturbance became highly likely after approximately 7–10 machine passes (Figure 3C–E).

Table 4. Logistic autoregressive mixed models describe the probability of peat surface disturbance. ROC represents the area under the receiver operating characteristic curve and indicates model classification performance. VIF (variance inflation factor) was used to assess multicollinearity among predictors.

Variable	Estimate	Stand. Error	df	t-/chi-Squared Value	p-Value	VIF
Model 1, ROC = 0.63						
Fixed effects						
(Intercept)	-1.838×10^{-0}	5.581×10^{-1}	376	−3.293	0.001	–
Number of passes	3.558×10^{-1}	1.029×10^{-1}	376	3.458	0.001 **	–
Random effects						
Sample plot variance	7.616×10^{-8}					
Phi	7.540×10^{-1}					
Dispersion	2.457×10^0					
Model 2, ROC = 0.60						
Fixed effects						
(Intercept)	-2.727×10^1	2.991×10^0	376	−9.117	<0.001	–
Cumulative total weight load, tons	2.978×10^{-1}	1.073×10^{-3}	376	277.570	<0.001 ***	–
Random effects						
Sample plot variance	5.070×10^2					
Phi	-6.074×10^{-1}					
Dispersion	1.210×10^{-3}					
Model 3, ROC = 0.67						
Fixed effects						
(Intercept)	6.614×10^0	2.159×10^1	372	0.306	0.760	–
Stand volume, m^3ha^{-1} (ref. V120 m^3ha^{-1})			2	1.836	0.399	1.14
V150 m^3ha^{-1}	5.048×10^0	1.100×10^1	52	0.459	0.648	
V180 m^3ha^{-1}	-1.156×10^1	1.285×10^1	52	−0.900	0.373	
Depth of ground water level, cm	-1.018×10^0	3.969×10^{-1}	52	−2.566	0.013 *	1.31
Number of passes	1.312×10^1	1.630×10^{-2}	372	804.559	<0.001 ***	1.00
Number of tree stems ha^{-1}	-1.339×10^{-2}	8.152×10^{-3}	52	−1.642	0.107	1.27
Depth of ground water level: Number of passes	-8.447×10^{-2}	2.910×10^{-4}	372	−290.634	<0.001	
Number of passes: Number of tree stems	3.170×10^{-4}	7.000×10^{-6}	372	44.993	<0.001	
Stand volume: Number of passes			2	110,370.000	<0.001	
V150: Number of passes	2.739×10^0	1.021×10^{-2}	372	268.170	<0.001	
V180: Number of passes	-1.465×10^{-1}	8.145×10^{-3}	372	−17.980	<0.001	
Random effects						
Sample plot variance	1.201×10^3					
Phi	-6.707×10^{-1}					
Dispersion	2.079×10^{-6}					

*, **, *** = statistical significance is <0.05, <0.01 or <0.001, respectively.

Rut depth was significantly affected by both stand and harvesting variables (Table 5). Among the stand variables, groundwater depth and peat layer thickness were significant predictors of rut depth. Among the harvesting variables, the number of passes and the number of ruts had significant effects. Because cumulative load was strongly correlated with the number of passes, their interaction term was used to account for multicollinearity.

Figure 4 illustrates the effects of stand and harvesting variables on rut depth in the 39 plots where rutting occurred. Rut depth decreased with increasing groundwa-

ter depth and increased with peat layer thickness (Figure 4A,B). Predicted rut depth also decreased as stem density increased, declining by approximately 5 cm between 1000 and 3000 stems ha^{-1} (Figure 4D). Among the harvesting variables, the interaction between cumulative load and number of passes had the strongest effect on rut depth (Figure 4E). In the 400-ton load class, rutting first appeared after approximately five passes, whereas rut depth increased more rapidly under lower cumulative loads.

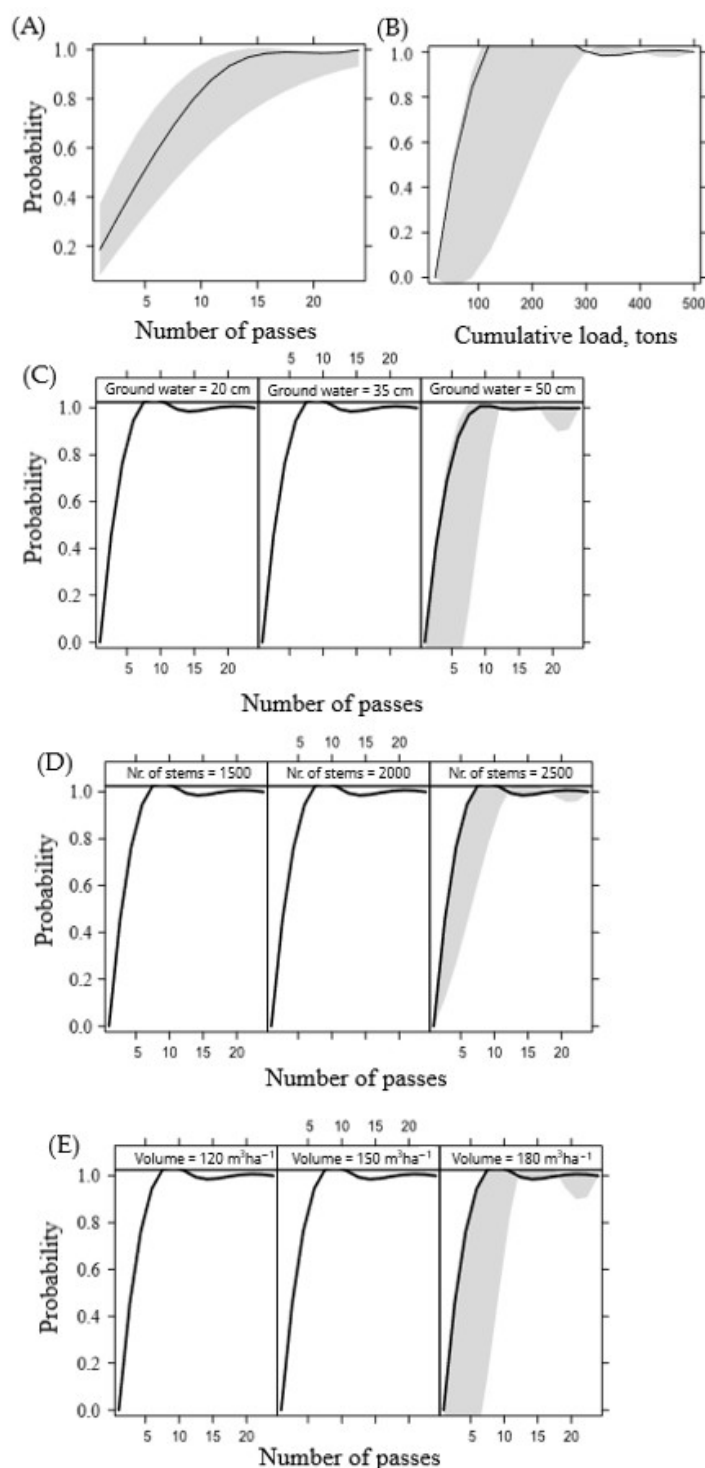


Figure 3. Predicted probability of rut formation from the linear mixed model in relation to (A) groundwater depth, (B) peat layer thickness, (C) number of ruts, (D) stem density, and (E) the interaction between cumulative load and number of passes. Predictions were calculated at the mean values of the other predictors. Shaded areas represent 95% confidence intervals.

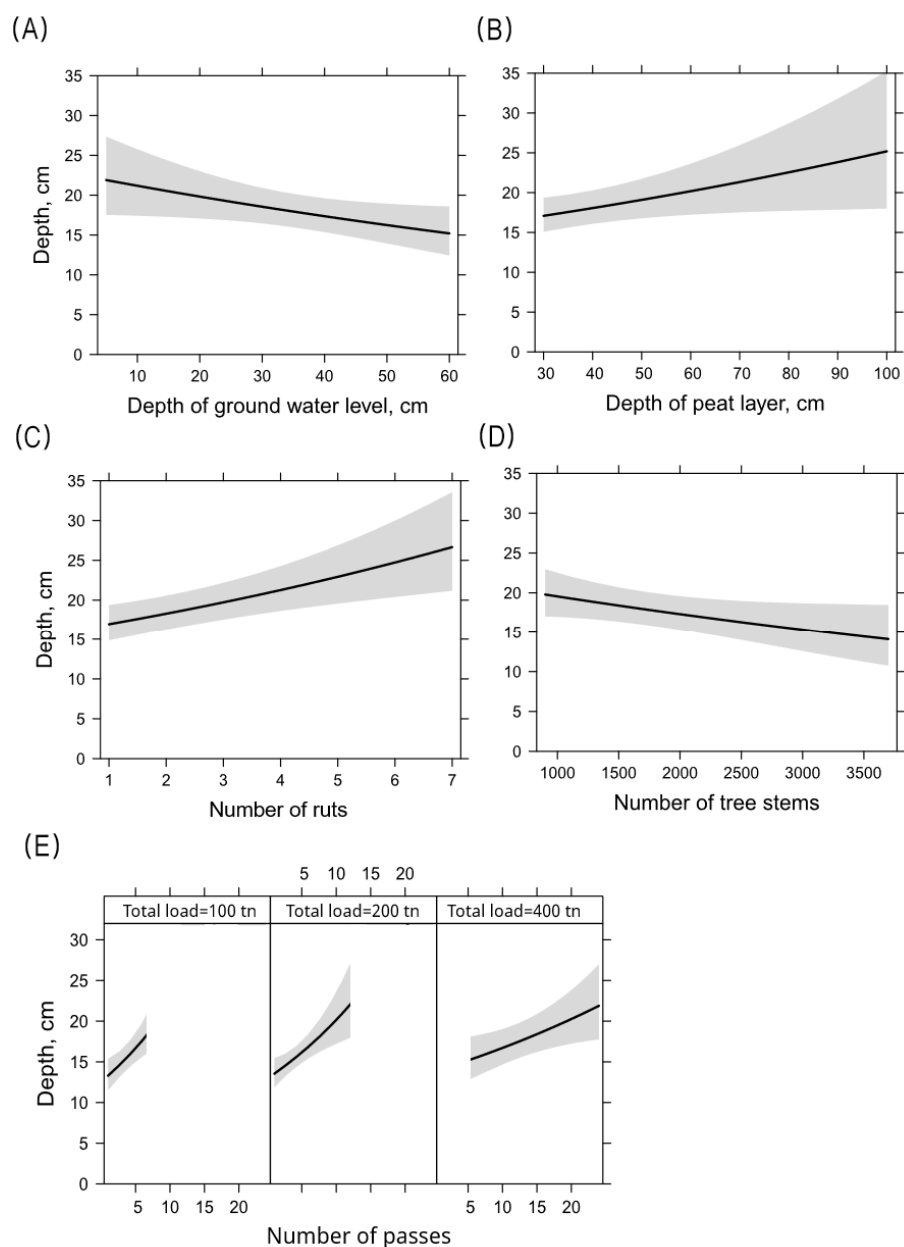


Figure 4. Predicted rut depth from the linear mixed model in relation to (A) groundwater depth, (B) peat layer thickness, (C) number of ruts, (D) stem density, and (E) the interaction between cumulative load and number of passes. Predictions were calculated at the mean values of the other predictors. Shaded areas represent 95% confidence intervals.

Table 5. General linear mixed model of rut depth (>0 cm) fitted using a log-normal distribution. VIF (variance inflation factor) indicates the degree of multicollinearity among the fixed effects. The marginal R^2 of the model was 0.35.

Variable Fixed Effects	Estimate	Standard Error	df	t-/Value	p-Value	VIF
(Intercept)	2.46×10^0	2.69×10^{-1}	177	9.159	<0.001	—
Depth of ground water, cm	-6.64×10^{-3}	3.27×10^{-3}	34	−2.029	0.050 *	1.56
Depth of peat layer, cm	5.55×10^{-3}	2.63×10^{-3}	34	2.105	0.043 *	1.54
Number of passes	6.91×10^{-2}	2.17×10^{-2}	177	3.181	0.002 **	3.03
Total cumulative load, tons	3.09×10^{-4}	4.40×10^{-4}	34	0.703	0.487	3.07
Number of ruts	7.54×10^{-2}	2.26×10^{-2}	177	3.335	0.001 **	1.23
Number of tree stems ha^{-1}	-1.21×10^{-4}	6.14×10^{-5}	34	−1.975	0.056	1.19

Table 5. Cont.

Variable Fixed Effects	Estimate	Standard Error	df	t-/Value	p-Value	VIF
Number of passes: Total load	-1.25×10^{-4}	4.79×10^{-5}	177	−2.597	0.010	–
Random effects						
Random part						
Sample plot variance	1.730×10^{-2}					
Residual	5.573×10^{-2}					
Phi	0.698					

*, ** = statistical significance is <0.05 or <0.01, respectively.

4. Discussion

Rut formation modeling was used to identify stand and harvesting factors associated with rutting during logging and forwarding on drained peatlands. In addition, rut development was modeled in relation to increasing machine passes and cumulative load. The results provide new information on how rut formation varied with machinery, road network planning, and operator decisions. The credibility of the principal findings was checked by the most important model diagnostics, such as convergence, singularity and outlier detection. These tests seemed appropriate (Supplementary File). The data is too small and local for larger generalizations or predictions. In addition, the operator's decisions might affect the results, and there was one study field in our data. Thus, it was not necessary to run comprehensive sensitivity analysis or validation (e.g., cross-validation), which are used in large-scale statistical analysis.

Rut depth measurements were conducted manually according to Finnish Forest Center guidelines [40]. Although uncertainties were associated with determining ground level and rut depth, the measurements followed standard Finnish inspection procedures. Unlike controlled experiments [19,21,32], this site-specific study was conducted under real-world operational harvesting conditions using a nine-ton forwarder, resulting in variation in load weights, machine passes, and site characteristics between sample plots.

Consequently, the results better represent practical forestry operations. The forwarder used was generally lighter than those reported in previous studies. In addition, the load weights of the forwarder were lower, resulting in lower cumulative total load weights on the forwarding roads. Because the objective of this study was to examine rut formation under practical harvesting conditions rather than under experimentally controlled traffic treatments, adaptive operator behavior formed an integral part of the operational system being investigated. Operator decisions regarding load size and forwarding strategy were associated with lower rutting on sites with poor bearing capacity. While this may have reduced the explanatory power of some models, it also reflects realistic harvesting practices where operators adapt to local conditions.

Rut depths were generally lower than those reported in previous studies for comparable numbers of machine passes [29,33], although the number of passes was higher. Poor bearing capacity was associated with high groundwater levels, thick peat layers, and low stand volumes. In the test plots characterized by these conditions (15 loads, $n = 32$), the operator adopted transport strategies aimed at minimizing ground loading. These test plots were mainly located on collector trails and along the edges of logging areas, where load collection was more frequently initiated. As a result, the cumulative load on these test plots remained below 100 tons, the average gross vehicle mass was 21.1 tons, and the number of passes varied from two to seven. These transport strategies therefore coincided with differences in load size, number of passes, and cumulative load, all of which are associated with reduced rut formation. Although operator-based adaptation may have reduced the

explanatory power of some models, it increases the practical relevance of the results by more accurately reflecting real harvesting conditions and operational decision-making in the field.

Under the conditions of this study, high stem density, birch-dominated stands, and abundant logging residues were generally associated with higher bearing capacity and lower rutting. The results indicate that peat thickness alone is not a sufficient predictor of bearing capacity [22]. Groundwater conditions, peat properties, vegetation, and logging residues were also associated with trafficability [8,10,14]. In eight plots, loading was initiated from areas where the negative effects of low bearing capacity were offset by high stem density [25], birch dominance, and large stand volume. In addition, crown biomass was significantly greater in these plots than the average for the dataset (7.6 vs. 3.7 dm³ m⁻² [23]). The results suggest careful harvest planning, operator decision-making, and the retention of logging residues may support harvesting on sites with low bearing capacity (e.g., the 100-t load class). However, these measures appear to be effective only for a limited number of machine passes; as the number of passes increases, rut depth tended to increase more rapidly.

Although crown biomass was not a statistically significant variable in the models, observations suggest that it may have contributed to reduced rut formation at several sites. These results are consistent with previous studies [23–25]. The slower increase in rut depth observed in the highest cumulative load class appeared to be primarily associated with more favorable site conditions rather than cumulative load itself. The plots in this highest load class were located on main roads, where factors reducing soil bearing capacity were less prevalent, allowing larger payloads and consequently higher cumulative loads.

Previous studies have shown that rutting generally increases with the number of machine passes [29,33]. In this case study, however, rut formation was influenced by a combination of site conditions, harvesting factors, road network planning, and operator decisions. The results suggest that successful forwarding is associated not only with limiting traffic but also with adapting operations to local bearing-capacity conditions [26,34]. In this study, road network planning was based on stand information, site visits, and airborne laser scanning data.

The objective of planning was to enable summer harvesting while minimizing forwarding distances and environmental impacts. Knowledge of peat properties, groundwater conditions, stand volume, and ditch network conditions proved useful for planning road locations and orientations. Following logging, the operator used observations of site conditions to adjust load sizes, forwarding order, and driving routes [28]. This tacit knowledge helped maintain access to areas with limited bearing capacity and reduced the risk of excessive rut formation.

Logging residues played an important role in reducing rut depths. Where residues were evenly distributed and road surfaces were relatively even, rut depths remained moderate despite repeated passes. In contrast, natural depressions, wet areas, and uneven road surfaces increased rutting even when residue cover was good. Overall, harvesting quality met Finnish legal requirements [40]. The findings highlight the potential importance of road network preplanning, adaptive forwarding practices, and the use of logging residues for limiting environmental impacts on drained peatlands.

5. Conclusions

This site-specific study identified and modeled the main predictors of rut formation and rut depth during summertime timber harvesting on drained peatland forests using a nine-ton forwarder. The most important predictors of rutting were the number of forwarder passes, cumulative traffic load, groundwater level, peat thickness, and interactions

between stand characteristics and harvesting variables. The results suggest that rutting was associated not only with traffic intensity and the forwarder's track equipment but also with local site conditions, road-network planning, and operator decisions. Under the conditions of this study, careful load management, adaptive forwarding strategies, and road-network planning were associated with lower rut formation, even under relatively high cumulative traffic loads. The findings highlight the importance of considering local site conditions when planning harvesting operations and suggest that operators' tacit knowledge may contribute to minimizing environmental impacts. Such knowledge could be incorporated into forest machine operator training and peatland harvesting practices.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/f17080925/s1>, Figure S1: Predicted probability of rut formation from the linear mixed model; Table S1: Sensitivity analysis for linear and logistic models; Table S2: Generalized linear mixed models.

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