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Physical Properties of Upper Mineral Soil Horizons in a Cutover Area of the Middle Boreal Forest in the Komi Republic

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Abstract—Changes in physical properties of podzolic soils (Albic Retisols) were analyzed three years after the cutting of the coniferous–deciduous forest in the middle boreal forest of the Komi Republic with three- and ten-times forwarder passes, as well as after leveling out the deep ruts left after ten passes. The study gained insight into an influence of the different numbers of passes on soil density, filtration coefficient, as well as resistance to wedging and compression. A hypothesis was made with respect to various mechanisms of soil changes—specifically, three forwarder passes lead to compression, while ten passes result in compression and turbation, which was confirmed by measurements of soil density and penetration resistance. After three passes, compression was found to lead to an increase in density by 0.15 g cm^{-3} and penetration resistance by 25%, No changes were recorded in filtration rate. Ten forwarder passes promoted mixing, which neutralized the possible compaction due to introduction of forest-floor detritus into the upper mineral soil horizons. Likewise, a decrease in penetration values occurred by a factor of 2 or 3 compared to an undisturbed site, and water permeability on a skid trail dropped from 70 to 1 cm day^{-1} after ten passes, It was found that leveling out the deep ruts led to an appreciable decline in soil density after 3 years, including in comparison with undisturbed soil of a cutting strip site. In addition, the filtration rate increased severalfold. Penetration resistance was, however, enhanced on the smoothed-out site. Estimation of the water retention curve approximation parameters by the van Genuchten formula made it possible to identify changes in soils of skid trails compared to a mechanically undisturbed site. Reduction in the range of mobile moisture was recorded as a result of compaction and ruts formed by heavy vehicles, resulting in stagnation of moisture in the ruts.

Keywords: Albic Retisols, density, moisture permeability, penetration resistance, water retention curve

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INTRODUCTION

Forests are an important part of the biosphere involved in climate control and organic matter production. Forest soils contain approximately 30% of the global carbon pool (Scharlemann et al., 2014). Logging is a major factor, affecting the forests (Bakhmet, 2014; Dymov, 2020). Cuttings substantially impact ecosystems, particularly in large forest regions, such as the Komi republic. At least a third of forested area was exposed to cutting in the Komi republic during the previous century (Il'chukov, 2012). Presently, the Russian Federation actively engages in logging, which is annually undertaken on thousands of hectares (*Gosudarstvennyi doklad*..., 2018). Timber harvesting technology has been considerably changing in the 21st century. Tree-length logging (stem-only harvesting) highly popular in a second half of the 20th century has been gradually replaced by cut-to-length technology based on the use of multioperational machines, such as harvesters and forwarders, which are heavy vehicles. Technologically, cutover area includes cutting strip sites, which have not been directly affected by the logging equipment, occupying large areas, and trails for timber skidding. Change in soils of the cutting strip sites was studied in enough details (Dymov, 2017, 2020; Karpechko, 2019; Telesnina and Shakhin, 1999). A number of studies have dealt with properties of soils of (skid) trails (Osipov et al., 2019; Dymov et al., 2022; Ilintsev et al., 2022); the physical properties (except the bulk density) have been, however, addressed in very few studies (Katarov et al., 2012). At the same time, studies report changes in the critical physical parameters of soils on skid trails and technological corridors (Wood et al., 2003; Cambi et al., 2016; Toivio et al., 2017). Heavy machines were found to have a significant effect on soil physical parameters, such as structure, porosity, and bearing capacity (Riggert et al., 2018; Huang et al., 2021). Bulk density, permeability, and penetration resistance reflect the state of habitats of living organisms, in particular, plants. The physical properties have optimums, going beyond the limits of which causes inhibition of growth and development in woody plants, while affecting the ecosystem regeneration. Additionally, a change in the physical parameters can transform the direction and intensiveness of water flows prevailing in the soil, as well as a number of the principal pedogenic processes. The impact of equipment on the physical properties of taiga soils has received almost no attention to date.

The goal of the study is to assess the physical properties of mineral horizons of podzolic soils taking into account different numbers of passes with heavy logging equipment and leveling out the deep ruts.

MATERIALS AND METHODS

Object of Study

The study was conducted in the Syktyvdinsky district of the Komi republic. The original forest featured coniferous–deciduous stands on podzolic soils. Felling was performed in December of 2020 using modern logging complexes. The considered total cutover area amounts to approximately 30 ha. Skid trails accounted for 17–18% of the total area. A PONSSE ELEPHANT ERG08W A090626 forwarder loaded with aspen pulpwood 36.3 t in total mass was used as an example to assess the impact of heavy equipment (vehicles). The major objects are represented by skid trails with three-time forwarder passes (3P) and ten-time passes (10P), as well as sites of the trails smoothed out after ten passes of the forwarder (10L). The leveling out includes cutting (leveling out) the ruts, as well as removal of the forest-floor detritus and cutting-wood debris to the nearby area. Therefore, nine skid trails, each 50 m long, were arranged with a soil pit made on each site, that is, 3P, 10P, and 10L. Additionally, the soil profile cut was made on a strip site (S), from which the trees are cut, but soils remain mechanically undisturbed. Physical properties were investigated in 2023 in June three years after the cutting. More detailed description of the experiment and changes in soils during the first year after the disturbance was previously presented by the authors (Dymov et al., 2022).

The investigated soil pits are outlined on Fig. 1. Soil on strip site features the profile structure O-EL1-EL2-BEL-BT and is classified under podzolic soil type. Soil of the trail with three-time forwarder passes (3P) has a structure similar to a cutting strip site; however, a rut with a depth of 11 cm was formed as a result of compression. Ten passes of the forwarder led not only to compression, but also mixing of the upper mineral horizons and forest-floor detritus; mean depth of the rut is 27 cm. The eluvial horizon was replaced by turbated horizon with inclusion of cutting-wood debris (TURcwd). It is gray in color due to introduction of organic material of the forest floor and abundant inclusion of branches, needles, cones, and occasional stones. Leveling out the ruts after ten passes with forwarder on a 10L site likewise induced a formation of turbated horizon, but without a considerable amount of wood debris (TUR). It partially retained the horizons EL and BEL, which can be fragmentarily diagnosed. Removed forest-floor detritus were pushed to the trails' sides. Therefore, soils of the site 10P and 10L were defined as turbozems. Names of horizons and soil types are assigned according to (*Klassifikatsiya i diagnostika pochv Rossii*, 2004), taking into account the recommendations on turbated soils (Dymov, 2020).

Study Methods

Soil density was determined by a drilling or boring method with three replicates, and the thermogravimetric method (Shein, Karpachevsky, 2007) was applied to consider moisture content. Texture was determined using a Mastersizer 3000e particle-size laser analyzer (Malvern Instruments, United Kingdom) preceded by destruction of aggregates with an ultrasonic dispersion energy of 450 J cm^{-3} (Yudina, 2020).

The filtration coefficient (Ks) was estimated by a constant head tube method in five replicates; the obtained data were approximated with the Horton equation. Penetration resistance of soils was assessed using an *MV*2 micropenetrometer (resistance to wedging) and Eijkelkamp Soil & Water penetrometer (resistance to compression) in ten replicates at a horizontal level (Shvarov et al., 2012). The aforementioned properties were determined in field conditions in the middle part of each selected genetic horizon. The water-retention capacity of soils was determined by centrifugation in three replicates (Shein and Karpachevsky, 2007); specifically, the collected bulk samples were first air-dried, then gently ground by rubber pestle, and screened through a 1-mm sieve. The RET-C program (van Genuchten et al., 1991) was used to compute approximation parameters of the van Genuchten formula (van Genuchten, 1980):

$$\Theta = \Theta_r + \frac{\Theta_s - \Theta_r}{[1 + (\alpha h)^n]^{1-\frac{1}{n}}},$$

where Θ (cm^3 cm^{-3}) is soil volumetric moisture content at an equilibrium point, h (cm of water layer) is matrix pressure (suction) of soil moisture, Θ_s and Θ_r (cm^3 cm^{-3}) are saturated and residual moisture capacity, respectively, α (cm^{-1}) is a value inverse to air-entry pressure, and n characterizes the slope of water retention curve.

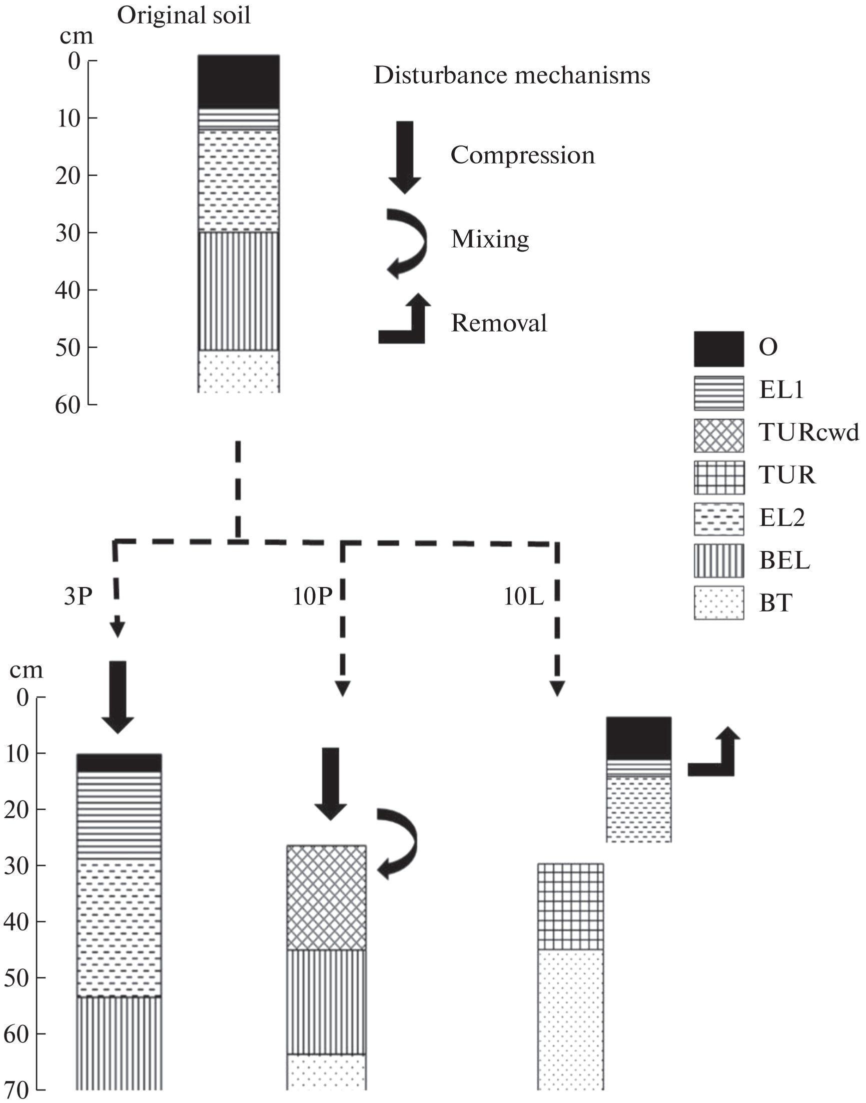

Fig. 1. Diagram of change in profile structure after the different number of forwarder passes: P, a cutting strip site of cutover area; 3P, skid trail with three passes; 10P, skid trail with ten passes; 10L, skid trail with ten passes and leveling.

The data were statistically processed in STATISTICA 2023. The distribution normality was checked by the graphic method Normal probability plot; since.in the case of resistance to penetration, sample size of the values was small and equal to ten. According to (Oreshkina, 1988), soil density was largely normally distributed. Therefore, the means and errors of the means were used to assess these parameters; means were compared using the *t*-test ($\alpha = 0.05$). Median values were employed for Ks and a water retention parameter. Next, Pearson's coefficient *r* was calculated to analyze correlations between density, as well as resistance to wedging and compression and the decimal logarithm of the filtration coefficient due to its lognormal distribution (Meshalkina, Samsonova, 2003).

RESULTS

The surface of an undisturbed strip site was taken as a datum level in constructing the profile distributions of the properties. On sites 3P and 10P, the soil surface corresponds to mean depths of ruts examined by us earlier (Dymov et al., 2022), that is, 11 and 27 cm, respectively. The soil surface of site 10L coincides with a depth of 30 cm.

Field study of the physical properties was conducted at the following bulk moisture content: (1) 22% in the upper and 15–17% in lower horizons on site P; (2) within a range of 15–18% in all horizons on site 3P; (3) at the same time, 17–19% on site 10P; and (4) 19% in the turbated and 25% in textural horizons of site 10L.

Soil Bulk Density

The results of soil bulk density investigation are shown in Fig. 2. The mean values are within a range of 1.6–2.01 g cm^{-3}, which falls outside a range of the typical bulk density values for loam soils (Shein, 2005). The high bulk density may be attributed to prevalence of micropores in the pore space and nearly entire lack of large interaggregate pores, which might be associated with characteristics of Quaternary sediments on the considered site. Soil of the strip site (S) is characterized by a gradual increase in bulk density from the upper to the lower mineral horizon (from 1.7 to 1.96 g cm^{-3}), which is common to texturally differentiated soils. Site 3P displays a remarkable increase in bulk density in the upper horizons, peaking at 2.01 g cm^{-3}, which is the maximum value, exceeding the value of textural horizons. The identified compaction on site 3P as compared with site P was statistically confirmed.

Soil bulk density in trail 10P, by contrast, is described by the slightly lower values (1.85–1.88 g cm^{-3}) compared to the BEL horizon of a cutting strip formed at the same depth, but with no significant differences between the means with these numbers of replicates. The least bulk density is recorded on the site 10L both from the turbated (1.6 g cm^{-3}) and textural horizons (1.62 g cm^{-3}), which do not significantly differ between themselves.

The following is based on the results of analysis of variance.

Texture

The relative content of size fractions of the primary soil particles is shown in Table 1. On the strip site, the upper horizon, which largely features a fine sand in its texture (27.44%), is lighter compared to the lower horizons, in which a coarse silt is dominant (29.94–30.32%). The physical clay maximum, accounting for 45.99%, is found within the BEL horizon.

The texture of an EL1 horizon on site 3P closely agrees with the data from the same horizon on strip site; ratio of sand fractions differs. Horizon EL2 proved to be the heaviest in the profile due to a large proportion of fine silt, equal to 25.24%. Fine sand, however, remains a dominant fraction in the entire profile (27.64–32.01%). The transitional horizon to the textural is slightly lighter due to ramp-up of coarse sand to 2.39%. As could be expected, the same horizon contains the largest proportion of the soil fractions <0.001 mm of 4.29%.

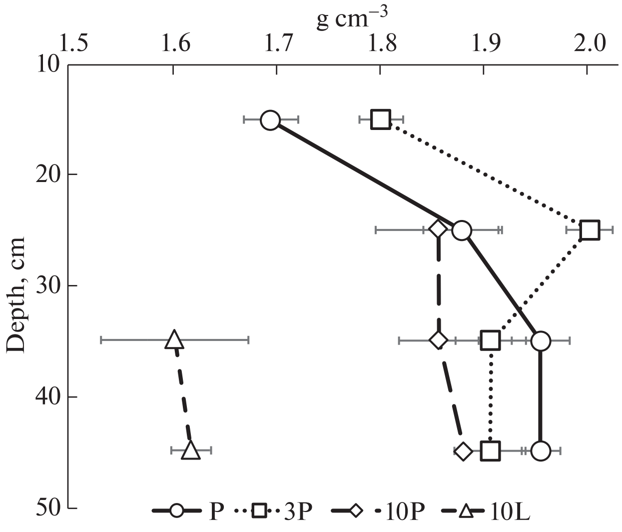

Fig. 2. Profile distribution of bulk density values: P, cutting strip site of cutover area; 3P, skid trail with three passes; 10P, skid trail with ten passes; 10L, skid trail with ten passes and leveling. Means ± error of the mean ($n = 3$).

A similar distribution is seen on site 10P. The turbated horizon, as well as all of the eluvial horizons described above, is dominated by a fine sand fraction with 28.18%. Heaviness in a BEL horizon is accompanied by an increase in the proportion of silty fractions; specifically, 26.82, 14.41, and 26.81% of the coarse, intermediate, and fine silt, respectively, and a fraction <0.001 mm of 4.22%. The content of fine silt is 35.45% and fractions <0.001 mm (6.27%) peaks in the textural horizon, which is the heaviest based on the texture of all the horizons in the investigated sites.

In a soil profile cut on 10P, gradient of the fractions' content is weakly marked due to removal of ruts in a process of leveling them out and exposure at the surface of the middle textural horizon or horizon transitional to it. The distribution of fractions is close to the one observed in a BT horizon of site 10P with dominance of coarse (24.95–25.32%) and fine silt (30.03–32.07%).

Filtration Coefficient

The median values of the filtration coefficient (Ks) and their variation is presented in Table 2. Generally, medians of Ks decrease down the profile on all sites to impermeable (restricting or preventing the permeability) levels.High filtration was recorded on strip site from an EL1 horizon by the Eggelsman classification (Shein, 2005). The median is 72 cm day^{-1}. All the underlying horizons are characterized by Ks values close to the impermeable based on this classification.

Particular replicates, however, display higher Ks values, which suggests that these horizons are permeable to water. The distribution pattern of the filtration capacity of soil on site 3P is analogous to the one described for soil of cutting strip.

The soil of the skid trail with ten passes is distinguished by extremely low filtration throughout the profile, in that median values of Ks in all horizons do not exceed 2.4 cm day^{-1}. Importantly, for all repli-

Table 1. Texture of studied soils

Site	Horizon	Depth, cm	Size fractions (mm) and their content, %							
			sand			silt			fragments <0.001	physical clay (<0.01)
			coarse (0.5–1)	medium (0.25–0.5)	fine (0.05–0.25)	coarse (0.01–0.05)	medium (0.005–0.01)	fine (0.001–0.005)		
P	EL1	10–15	3.45	10.20	27.44	26.86	12.45	18.42	1.18	32.05
	EL2	15–33	1.79	5.31	23.37	30.13	15.11	22.79	1.50	39.40
	BEL	33–55	0.01	2.40	21.66	29.94	15.78	26.91	3.30	45.99
	BT	55–65	0.81	2.05	21.70	30.32	15.38	26.29	3.45	45.12
3P	EL1	15–20	1.99	7.66	32.01	26.38	12.11	18.67	1.18	31.96
	EL2	20–40	0.37	4.30	28.87	25.01	13.54	25.24	2.67	41.45
	BEL	40–60	2.39	5.35	27.64	24.89	12.15	23.29	4.29	39.73
10P	TURcwd	25–40	4.87	8.30	28.18	25.61	11.95	19.61	1.48	33.04
	BEL	40–65	0.26	4.10	23.38	26.82	14.41	26.81	4.22	45.44
	BT	65–85	2.96	3.50	12.36	24.23	15.23	35.45	6.27	56.95
10L	TUR	30–50	2.64	4.94	18.80	24.95	14.18	30.03	4.46	48.67
	BT1	50–85	1.68	3.85	16.57	25.32	15.04	32.07	5.47	52.58

P, cutting strip site of cutover area; 3P, skid trail with three passes; 10P, skid trail with ten passes; 10L, skid trail with ten passes and leveling.

cates, an entire lack of filtration is only observed in the horizon TURcwd, which, therefore, can be considered impermeable.

On site 10L, a filtration rate of the upper mineral horizon is characterized by the maximum values among all the investigated horizons; the median is 180 cm day^{-1} (very high filtration by Eggelsman). Filtration coefficient of a TUR horizon exceeds values of upper horizons on strip site two- to fourfold.

Resistance to Wedging

Data on resistance to wedging at the horizontal levels are shown on Fig. 3.

An increase in the penetration resistance with depth is observed on strip site. The value of resistance to wedging of 82 kPa measured in an EL1 horizon is the lowest among all horizons of the other sites. The absolute maximum 328 kPa was, however, recorded from a BEL horizon at depths of 35–45 cm.

The general trend on site 3P is analogous to the one described on strip site. The mean of resistance to wedging is, however, significantly higher in an EL2 horizon: it measures 277 kPa. This is the maximum value among eluvial and turbated horizons. The difference is not statistically significant with this number of replicates.

Site 10P is characterized by relatively low values of 97 and 89 kPa in the TUR and BEL horizons, respectively. In terms of the considered parameter, the turbated horizon is comparable to an eluvial horizon on the strip site; no significant differences were found. A decline in the penetration resistance was, however, statistically confirmed when taking into account the rut depth and when comparing it with the BEL middle horizon of the strip site.

Level of resistance to wedging among upper horizons was recorded to be the highest from the site 10P. It is equal to 315 kPa, which approximates it to the underlying textural horizons.

Table 2. Filtration coefficient of genetic horizons

Site	Horizon	Depth, cm	Filtration coefficient, cm day^{-1}		
			median	minimum	maximum
P	EL1	10–15	72	2.4	360
	EL2	15–33	2	2.0	60.8
	BEL	33–55	2.4	2.0	24.5
	BT	55–65	2.4	2.4	302.4
3P	EL1	15–20	65.4	4.9	446.4
	EL2	20–40	2.6	2.4	29.8
	BEL	40–60	2.4	1	39
10P	TURcwd	25–40	1	1	1
	BEL	40–65	2.4	2.4	157.5
	BT	65–85	2.4	2.4	7.5
10L	TUR	30–50	180	53.8	460.8
	BT1	50–85	2.4	2.4	26.9

P, cutting strip site of cutover area; 3P, skid trail with three passes; 10P, skid trail with ten passes; 10L, skid trail with ten passes and leveling. Medians ± range of values ($n = 5$).

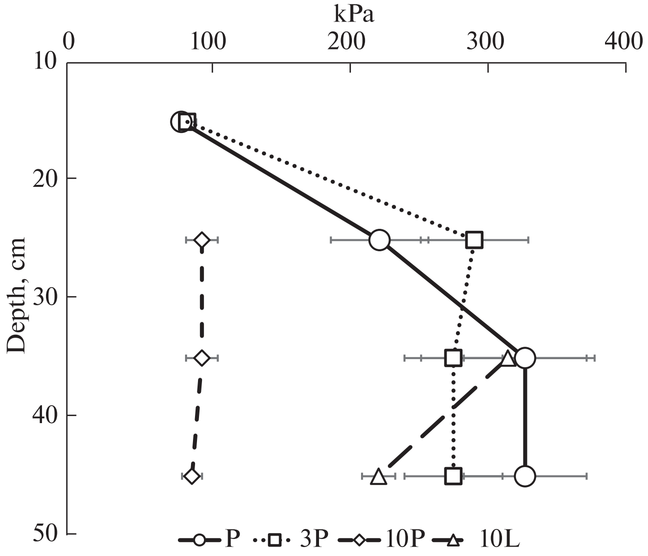

Fig. 3. Profile distribution of wedging resistance values at horizontal levels of genetic horizons: P, cutting strip site of cutover area; 3P, skid trail with three passes; 10P, skid trail with ten passes; 10L, skid trail with ten passes and leveling. Means ± error of the mean ($n = 10$).

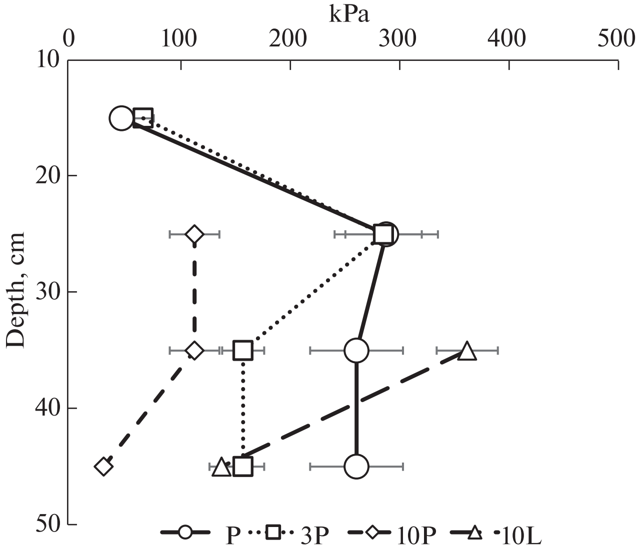

Fig. 4. Profile distribution of compression resistance values at horizontal levels of genetic horizons: P, cutting strip site of cutover area; 3P, skid trail with three passes; 10P, skid trail with ten passes; 10L, skid trail with ten passes and leveling. Means ± error of the mean ($n = 10$).

Resistance to Compression

Changes in resistance to compression at horizontal levels are reported in Fig. 4. The obtained values range from 49 to 362 kPa.

Soil of strip site is characterized by a significant increase in its resistance to compression in the upper 30 cm with the values of 49 and 287 kPa in the EL1 and EL2 horizons, respectively. Further downward, the values slightly decrease with depth to 262 kPa.

No appreciable differences were found in soil of site 3P compared to strip site soil. At the same time, site 10P markedly exhibits a relatively low penetration resistance throughout the entire profile, not exceeding 116 kPa, which was statistically confirmed by comparison of the means. The EL2 and BEL horizons at the same depth on the strip site soil are characterized by a value exceeding the above-reported value more than twice.

The maximum resistance to compression is observed in turbated horizon of site 10L, where it averages 362 kPa. A difference between this horizon and the BEL strip site horizon, lying at the same depth, could not be statistically proved. In the underlying BT horizon, the penetration resistance decreases to one comparable to values of the other sites. Therefore, no increase in resistance to compression was recorded from soils of skid trails compared to the undisturbed soil of strip site. A statistically significant reduction in penetration was found after ten passages.

Parameters of Water Retention Curve

Median values of approximation points of water retention curves are presented in Table 3. Residual moisture content Θ_r was not calculated.

In strip site soils, Θ_s and α are higher than in skid trails. Sharp drop in these parameters in the EL2 horizon down to 30.29% and 0.02 cm^{-1} is rather abnormal. At the same time, n has the highest value in the profile (1.27). In the textural horizon, α increases by more than twice compared to the upper horizons.

All soil horizons of skid trails are characterized by a decline in Θ_s from the upper to lower horizons, whereas the reduced (compared to a cutting strip) α values are more homogenous inside the profile. The general upward trend with depth, however, persists.

The high value of n in an EL1 horizon of site 3P is rather abnormal. The upper turbated horizon of a site 10P soil differs little from eluvial horizon of cutting strip soil. The parameter values at transition to a BEL horizon are closer to the observed on the other mechanically disturbed sites.

DISCUSSION

Differences in physical properties were found between skid trails and undisturbed sites. Soil density, water permeability, and penetration resistance are extremely sensitive to various disturbances. Three passes with a forwarder lead to compression of the upper genetic horizons. This type of disturbance considerably increases the density, which agrees with the results of other studies concerned with soils, undergoing changes after the use of forwarders (Karpechko, 2019; Toivio et al., 2017). Another trend was revealed on the site 10P, on which mixing of mineral horizons, forest-floor materials, and cutting-wood debris occurred in additions to compression. These processes in combination led to formation of a TURcwd horizon in place of the O, EL1, and EL2 horizons. The density of this horizon is 0.16 g cm^{-3} higher than the upper portion of eluvial horizon of the site P soil, which confirms an occurrence of the over compaction, which was also recorded for a smaller number of forwarder passes. It is important, however, to consider a depth of the formed rut, which is comparable to thicknesses of the upper soil horizons on the strip site and averages 27 cm. No significant differences were found as a result of a comparison between the density of that same horizon TURcwd and EL2 of the strip site, lying at a depth of 15–33 cm. In fact, the values on site 3P are considerably higher at the same depths, which suggests a slight decrease in density with an increase in the number of forwarder passes in association with turbation processes The similar trend is described in the study (Katarov et al., 2012) conducted in the Republic of Karelia and Tver oblast, in that the initial five passes with a forwarder induced an increase in density, whereas the density gradually declined with a larger number of passes. Importantly, the values still exceeded the background after ten passes.

In earlier soil density investigations (Dymov et al., 2022) conducted 6 months after the cutting, upper horizons are characterized by values lower than the ones obtained in the present work. Temporary moisture stagnation appears to be a rather important factor in a density increase three years after the cutting. The observed compaction after two-and-a-half years was reported in (Karpechko, 2019); the original forest likewise was represented by “green moss” spruce stands. In addition, this author points out a further downward density trend with time elapsed after the cutting. A surface of a TUR horizon appears to be more exposed to the ambient environment due to a complete lack of vegetation on skid trail; therefore, the loosening proceeds more actively and over a shorter time span, resulting in the relatively low density values 1.62 g cm^{-3}.

Texture primarily ranges from medium loam, becoming heavier in textural horizons, to light clay on site 10P. The content of the fraction <0.001 mm increases with depth both on strip site and skid trails. At the same time, the physical clay maximums on sites P and 3P are found in the middle of the profile and associated with an appreciable increase in fine silt fraction. Similar fraction ratios of the TUR and BT horizons on site 10L is not unexpected, since leveling out led to a complete removal of upper horizons, which resulted in exposure at the surface of the lower textural horizons only slightly different from each other.

Table 3. Approximation parameters of water retention curve

Site	Horizon	Depth, cm	Θ_s, %	α, cm^{-1}	*n*
P	EL1	10–15	40.06	0.117	1.24
	EL2	15–33	30.29	0.019	1.27
	BEL	33–55	37.63	0.117	1.14
	BT	55–65	41.71	0.270	1.11
3P	EL1	15–20	29.49	0.015	1.65
	EL2	20–40	28.60	0.032	1.26
	BEL	40–60	29.22	0.057	1.26
10P	TURcwd	25–40	38.56	0.018	1.24
	BEL	40–65	27.61	0.076	1.20
	BT	65–85	19.44	0.025	1.20
10L	TUR	30–50	32.77	0.046	1.28
	BT	50–85	24.89	0.087	1.15

P, cutting strip site of cutover area; 3P, skid trail with three passes; 10P, skid trail with ten passes; 10L, skid trail with ten passes and leveling. Medians (repetitions = 3).

Particular differences in the texture as compared with the results obtained 6 months after the cutting (Dymov et al., 2022) might be attributed to distinctions between methods for determination of texture. However, importantly, the main patterns of distribution of fractions throughout a profile agree with the previously obtained results.

The rate of filtration is found to change after ten forwarder passes. An upper TURcwd horizon is an impermeable layer, which can lead to prolonged moisture stagnation in ruts in spring and fall periods. The lower horizons likewise exhibit impermeable median values of the filtration coefficient. The pronounced permeability impairment can be associated with several factors. First, rut formation induced exposure at the surface of the horizons, which rate of filtration on strip site corresponds to impermeable layer. Second, rutting from the forwarder appears to have led to strong reduction in the number of pores capable of propelling moisture even at a low rate. No significant differences were recorded between the cutting strip and skid trail after three passes, which can be attributed to a relatively low depth of the rut, the surface of which coincides with the eluvial horizons of the strip site. Reduced filtration in skid trails agrees with the data (Wood et al., 2003) recorded from peaty gley soils. The turbated horizon on site 10L is distinguished by very high permeability, which is apparently due to an occurrence of cracks, which conduct moisture by preferential flows through macropores. Importantly, upper mineral horizons are entirely exposed at the surface on this site. Removal of the forest-floor detritus appears to result in more appreciable amplitudes of moisture and temperature (Dymov, 2020). These soils are characterized by extreme desiccation and temporary excessive moistening, as well as more active sea-

Table 4. Pearson correlation coefficient

		1	2	3	4
1	Density	1			
2	Wedging resistance	0.18	1		
3	Compression resistance	0.1	**0.88**	1	
4	$\log_{10}$Ks	**−0.58**	−0.05	0.13	1

P, cutting strip site of cutover area; 3P, skid trail with three passes; 10P, skid trail with ten passes; 10L, skid trail with ten passes and leveling. Coefficients that are significant for this sample size (n = 15) are set in bold.

sonal processes of freezing and thawing compared to other sites investigated in this work.

A significant change in penetration resistance has been found on skid trails. After ten passes, a the TUR horizon in skid trail soil is characterized by a decrease in penetration parameters, possibly due to enrichment of the EL1 mineral material with forest-floor detritus, which is consistent with rather low density of the same horizon. The turbated horizon of the site smoothed out after ten passes, by contrast, features high values of compression resistance, inappreciably exceeding the values of textural horizons on the other sites. No differences in compression values were found between cutting strip and site 3P. The differences obtained in earlier studies were assessed as statistically insignificant (Wood et al., 2003). Therefore, penetration resistance appreciably changes either downward after ten passes with a forwarder or upward after three passes; the latter is characteristic precisely of wedging resistance.

Table 4 lists values of the correlation coefficient. A statistically significant inverse correlational relationship was established between the density and Ks (r = −0.58), which is predictable, since the compaction caused by external disturbances leads to a decrease in soil porosity, resulting in reduced filtration rates. Additionally, a direct relationship exists between the resistance to compression and wedging resistance (r = 0.88).

The soil water retention parameters on the trails differ from on the strip site. A decline in saturated water capacity in conjunction with the originally low values of n narrows the mobile moisture range, which is consistent with data on reduced filtration.

CONCLUSIONS

The physical properties of podzolic soils are highly sensitive to mechanical disturbance and subsequent change in the water and temperature regimes in the course of the 3-year period of the regeneration succession. The number of passes, rutting and turbation intensity, and activities on leveling out the ruts with removal of upper horizons govern the physical properties of the upper horizons and their subsequent functioning. Soil rutting, which is the most clearly evident as a result of three forwarder passes, triggers an increase in density and wedging resistance, as well as change in water retention capacity in the upper 30 cm of soil. At the same time, both the compression resistance and the filtration rate remain stable. In addition to rutting, ten forwarder passes cause turbation of the upper mineral horizon, forest-floor detritus, and cutting wood debris. A rut depth estimation is critical in assessment of change in physical properties. The mixing inappreciably affected soil density, whereas penetration resistance values and filtration coefficient significantly decreased.

Leveling the skid trails, that is, removal of the upper horizons to a depth of approximately 30 cm, on the contrary, led to a relative decrease in density and appreciable gain in filtration coefficient in conjunction with improved resistance to compression in the upper horizon. The primary reason for these changes is associated with exposure at the surface of textural horizons and their sensitivity to environmental effects, consisting in freezing–thawing and wetting–desiccation processes, which results in a change in the porous space likely due to an increase in volume occupied by large interaggregate pores.

The reported change in water retention parameters recorded from all disturbed sites indicates a curve flattening, which, in conjunction with the low filtration and heavy texture identified on skid trails, is a condition for stagnation of moisture. In addition, skid trails appear as microdepressions relative to the undisturbed surface of the cutting strip, which further enhances the overmoistening.

Investigation of the physical properties allows a short-term assessment of changes as a result of exposure to logging equipment, since the bulk of the work is carried out directly in field conditions.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any studies involving human and animal subjects.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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