DEGRADATION, REHABILITATION, AND CONSERVATION OF SOILS

Changes in Soil and Vegetation with Different Number of Passes of Wheeled Forestry Equipment (Middle Taiga, Komi Republic)

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Abstract—Changes in podzolic soils (Albic Retisols) and vegetation after felling blueberry spruce forest in the middle taiga of the Komi Republic are discussed. Changes in the morphological and physicochemical properties of soils after three and ten passes of the forwarder, as well as after ten passes with subsequent leveling of the ruts are characterized. It is shown that the number of forwarder passes is the decisive factor in soil changes. At the site with three passes, the formation of ruts with a depth of 11 ± 3 cm is observed, while at the site with ten passes, the depth of the ruts can reach 66 cm with an average value of 27 ± 4 cm. Leveling of forwarding trails to remove the ruts leads to the greatest transformation of the natural composition of the upper soil horizons over a larger area. A significant increase in the bulk density of the upper mineral horizon of the soil of the trail takes place after three passes. After ten passes, the bulk density of the upper mineral horizon decreases because of its mixing and loosening by wheeled vehicles. At the same time, an increase in the bulk density of the underlying middle-profile mineral horizon retaining its natural composition is observed. The upper horizons of the soil of the trail leveled with the use of an excavator are characterized by a significant increase in the bulk density compared to the initial soil. It was found that the regrowth of the main tree species in the first year after felling is extremely uneven. In the case of a strong clutter on the trails, there is no regrowth, which requires additional measures to improve tree growing these technological elements of felling area. On the leveled areas of the trails, the absence of regrowth in the first year after felling was observed. However, it can be assumed that in the future these areas will be fairly quickly populated with regrowth of tree species.

Keywords: soil compaction, track leveling, felling, Retisols, field experiment **DOI:** 10.1134/S1064229322110023

INTRODUCTION

Economic activity of humans is the leading factor of changes in boreal forests. Forest ecosystems of the Komi Republic (RK), as well as other taiga ecosystems of Russia, have been subjected to increasing anthropogenic impact since the 17th–18th centuries [24]. At the same time, until the middle of the 20th century. sparing approaches to logging activities, including manual logging and horse hauling of wood, did not lead to significant changes in the species composition of forests. In large areas covered by such types of logging, coniferous phytocenoses functioned close to their natural functioning patterns [23]. The situation began to change from the middle of the twentieth century. Thus, over 60 years, 112000 km² of the RK have been affected by industrial felling and 1 billion m³ of wood has been harvested [4].

The increase in the volume of harvested wood, the mechanization of the logging process, the predominance of clear concentrated and clearcut felling contributed to the intensification of the anthropogenic impact on taiga ecosystems. The forest cover pattern [31], the cycle of biophilic elements [5, 14, 32], and the microclimatic parameters of soils [16] change in the areas that have been felled. On a large area of the European northeast of Russia, coniferous trees have been replaced by deciduous trees [8, 23, 26]. Plants of the ground cover are sensitive indicators of environmental changes in felling areas [11, 22, 44]. Logging technologies largely determine the composition and structure of derived plant communities [27, 43]. In the taiga zone, the transformation of the micro- and mesorelief under the impact of heavy logging machines leads to the appearance of new complex vegetation communities with a high degree of heterogeneity on clearings [29].

Clearcutting is the most widespread logging method in the European north of Russia [25, 26, 39]. Technologically, with such types of felling (regardless of the type of timber skidding), areas are separated that differ in the nature of the impact on ecosystems. The least disturbed areas (residual plots) occupy 59-71% of felling sites. Areas with disturbances of the soil cover during skidding and storage of wood are allocated to skidding trails (or technological corridors) occupying 18-29% and loading plots (6 to 15%) [33]. In some cases, disturbance of the soil surface occurs on 40-60% of the cutting area [17]. In areas, where artificial reforestation is planned, the area of soils with mechanical transformation associated with the preparation of soils for tree planting may be even larger [42].

At present, tree-whip hauling is gradually being replaced by Scandinavian technology, which includes the use of multi-operation machines (forwarder¹ and harvester). A significant number of logging enterprises carry out timber harvesting by multifunctional complexes. In the KR, where these studies were carried out, the ratio of harvesting using Scandinavian and traditional (skidder and chainsaw) technologies is 90 and 10%, respectively. According to the existing requirements for the organization and performance of timber harvesting [37], the share of portages and timber loading areas when using multioperational equipment can be up to 30% of the total cutting area. At the same time, the depth of the ruts is not regulated in this document. According to our preliminary estimates, the areas of mechanically disturbed soils rarely exceed 20% of the cutting area [14]. Currently, there are few works on the assessment of the impact of harvesters and forwarders on the soils of Russia [15, 18, 21, 30]. In contrast to the Scandinavian countries and regions of the Russian Federation with similar forest conditions [12, 28, 46], the effect of the cut-to-length technology of timber hauling on soils virtually has not been studied. It is likely that significant differences compared with European countries [45, 47] and Karelia [12, 28] in logging in similar forest types will be determined by the characteristics of the bearing capacity of soils, namely, their texture and high water content.

The purpose of this study is to evaluate changes in soils and vegetation when using heavy wheeled logging equipment.

Research objectives: to evaluate changes in the morphological and physico-chemical properties of soils with a different number of forwarder passes, as well as with surface leveling and removal of deep ruts; to identify changes in the composition of plant communities of different technological elements of felling; and to characterize the features of reforestation in the studied areas.

OBJECTS AND METHODS

Description of the field experiment. For the experiment, in the spring of 2020, a plot of blueberry–greenmoss spruce forest was selected in Syktyvdinsky district of the KR (Fig. 1). The study of the initial forest area (IF) began in the spring of 2020. The climate of the study area is moderately continental and moderately cold [2]. The mean monthly air temperature in July is $+16.6^{\circ}$ C. The mean annual temperature is $+0.4^{\circ}$ C, and the mean annual precipitation is 514 mm [2].

According to the soil-geographical zoning of the KR [3], the study area is located in the southern part of the Vym–Vychegodsky district of typical podzolic soils, iron-illuvial podzols, and humus-illuvial gleyed peat-podzolic soils. The study objects were located at the top of the moraine ridge. The topographic survey was conducted using a Vega L32C level. The terrain map was built using Surfer software (Golden Software Inc.). The features of the relief are shown in Fig. 1.

The logging in the study areas was carried out on December 7–8, 2020. A four-axle PONSSE ELE-PHANT ERG08W A090626 forwarder with a standard weight of 22.8 tons was used as an experimental machine. The pressure in the wheels was 3.5 (front wheels) and 5.5 (rear wheels) bar. Standard removable metal tracks were used only for the rear wheels. Before passing, the forwarder was loaded with aspen logs; the diameter of each log was measured, and the volume of wood was calculated (Fig. 2). The total weight of the forwarder with wood was 36.3 tons.

By the time of felling, the forest area under study had virtually ideal conditions: the absence of prolonged snowfalls before felling, stable subzero air temperatures, which allowed the soils to freeze to a depth of about 15 cm, which in turn ensured a high bearing capacity of the soils. At the time of the experiment, the air temperature was -3.2° C, and the litter temperature was -0.5° C.

During the experiment, nine trails were laid on the top of the ridge, each about 50 m long. The number of forwarder passes was three (3P) on three trails and ten (10P) on six more trails. Soil pits were laid in the ruts, the inter-rut space was not mechanically disturbed. On three trails with ten forwarder passes, the ruts were leveled (10P); and litter, stumps, and logging residues were removed (shifted to the edge). Litter and logging residues were moved onto the area adjacent to the trails. Leveling was carried out with a Komatsu PC-8 excavator the next day after felling. A series of leveled trails (10Pl) was made to assess the feasibility of using leveling technology for the success of subsequent reforestation. The trails were not strengthened with logging residues. Immediately after felling (December 2020), measurements were made of the depths of the ruts formed by heavy wheeled vehicles. Measurements were taken every 2.5 m. For 3-pass trails (with two ruts each), 162 measurements were made; 392 measurements were made on 10-pass trails.

The assessment of morphological changes in soils and soil sampling were carried out in July 2021. One reference soil pit was laid on each kind of soils. The classification position of soils was determined according to [36] taking into account recommendations for

¹ Forwarder is a machine that skids wood; harvester is a machine that cuts and lays wood on the surface of the soil.



Fig. 1. Location of the study site and scheme of trails.

assessing the properties of turbated soils [13, 14]. To determine the color of genetic horizons, the Munsell scale was used. The bulk density in organic and mineral horizons was determined in reference pits according to [7]. The main properties of the soils of felling areas were determined in samples taken in July.

The chemical analysis of soils was carried out in an accredited ecoanalytical laboratory and the department of soil science of the Institute of Biology of the Komi Scientific Center of the Ural Branch of the Russian Academy of Sciences. The total contents of carbon and nitrogen were determined on an analyzer EA-1100 (Carlo Erba). The pH of water extracts was assessed using an Edge HI2002-02 pH meter (Hanna Instruments, Romania) at the soil / solution ratio of 1:25 for litter and 1 : 2.5 for mineral horizons. Exchangeable cations were extracted by ammonium acetate extract (pH 7) with subsequent determination on an ICP Spectro Ciros atomic emission spectrophotometer. The particle-size distribution was determined according to the Kachinskii method. The contents of iron and aluminum soluble in an acidic ammonium oxalate solution was measured by atomic emission spectrometry. To extract nonsilicate iron compounds from the soil, regardless of the degree of crystallization, the Mehra– Jackson method was used [41]. The Schwertmann coefficient was calculated according to the equation: $K_{sh} =$ Fe_{ox}/Fe_{dith} [10]. Phosphorus was determined according to standard procedure PND F 16.1:2.3.11-98 [38]. The method involves soil treatment with 5M HNO₃ (2 g soil/10 cm³ acid) followed by heating in a water bath for three hours and determination on an ICP Spectro Ciros spectrophotometer.

When describing plant communities, methods were used that are generally accepted in geobotany and forest typology [19]. On each test plot, the composition and density (in fractions of a unit) of the forest stand and undergrowth were taken into account. For the grass-shrub and moss-lichen layers, the total projective cover was determined in percent, and the degree of species dominance was assessed using the Ipatov dominance scale [19]. In order to identify the biodiversity of plants, the α -diversity index and species saturation were calculated.

On the control plot of the blueberry–green-moss spruce forest, one description of the original forest



Fig. 2. Loading the forwarder before the experiment.

community was made (size 20×20 m). In the cutting area, vegetation cover was recorded at each technological element. The size of the test plots (**TS**) in the residual part of the forest stand was 5×5 m. On leveled trails and in ruts, the vegetation was taken into account through survey along each technological element. Latin names of taxa of vascular plants and mosses were given according to the web source worldfloraonline.com; lichens were named according to Santesson et al. [48].

Forest regrowth was assessed according to Pobedinsky [34]. In the clearing, trial plots (TPs) of 1×1 m in size on each technological element (residual forest. skidding trails) were surveyed. Overall, data from 56 TPs were obtained. A detailed description of the regrowth of the trees of different species was carried out on TPs [40]. On the TPs laid on skidding trails, the width and depth of the ruts were additionally measured, the presence or absence of water in the ruts, and the amount of logging residues were noted. The young growth occurrence index (*t*) was determined as the ratio of the number of TPs with young growth (n_{gr}) to the total number of surveys TPs (n_{tot}):

$$t = n_{\rm gr}/n_{\rm tot}$$
.

At t > 0.65, the distribution of young growth is considered uniform and additional measures aimed at improving the reforestation process are not required. At $t \le 0.65$, the distribution of young growth is uneven and additional measures are required to improve regrowth; if natural regrowth is absent, artificial forest planting should be applied.

The calculation of the average height of coniferous and deciduous regrowth was carried out separately on trails, residual plots, and in general on clearings. The assessment of the degree of confidence and in-depth analysis of survey materials on the conservation of regrowth or measures to promote natural regeneration was carried out using methods of mathematical statistics.

RESULTS AND DISCUSSION

Changes in vegetation cover on the main technological elements of felling area. The original community was represented by an uneven-aged coniferous-deciduous plantation, passed through ground fires and selective felling of large coniferous trees about 60 years ago. The tree layer is formed by Scots pine (*Pinus syl*vestris L.), Siberian spruce (Picea obovata Ledeb.), birches (*Betula pubescens* Ehrh. and *B. pendula* Roth.), Siberian fir (*Abies sibirica* Ledeb.), and aspen (*Populus* tremula L.). The forest stand formula is 4P3S2B1A solF. Layering in the forest stand is not expressed. Dead wood occurs mainly in coniferous stands with a stem wood stock of 30 m³/ha. The undergrowth is dominated by spruce with a small admixture of birch and aspen. The total projective cover (TPC) of the grass-dwarf shrub layer is 80%; it is dominated by bilberry (Vaccinium myrtillus L.). The TPC of the mosslichen layer is 80%; Hylocomium splendens (Hedw.) Schimp. predominates; Pleurozium schreberi (Willd. ex Brid.) Mitt., Sphagnum angustifolium (Warnst.) CEO Jensen, and Polytrichum commune Hedw. are common moss species.

Compared to the initial communities, the shrub layer in felling becomes depleted (Table 1). Its density decreases, and juniper (Juniperus communis L.) disappears from it. Large shrubs were destroyed during felling, so the height of plants in the post-cutting areas of residual plots decreases to 30–40 cm. The total species diversity of vascular plants decreases insignificantly (from 18 species on the control plot to 16 species in the felled area). Blueberries retain the leading cenotic positions. Changes in the light regime lead to an increase in the abundance of light-loving species (lingonberries Vaccinium vitis-idaea L., meadow grass Deschampsia flexuosa (L.) Trin.), Maianthemum (*Maianthemum bifolium* (L.) FW Schmidt), one of the dominant species in herb-shrub layer of control plots, being a more shade-tolerant species, reduces its abundance on clearings.

The total projective cover of the herb-shrub laver in the residual plots decreases to 15-30% compared to 80% at the control. The projective cover of the mosslichen laver somewhat decreases within residual plots (40-60% vs 80% at the control). The main changes take place in its composition, where species of moist habitats (Sphagnum angustifolium and Polytrichum commune) become dominants. The abundance of mesophytic species Hylocomium splendens decreases from 8 to 4–6. The effect of increased moisture content in clearcut habitats is well known from the literature [22, 27, 43]. As a result of the destruction of trees, which are powerful pumps that pump water out of the soil, the hydrological regime changes at the initial stages of ecosystem restoration, and temporary waterlogging is developed.

After the forest felling, six moss species were recorded in the studied area; the average α -diversity of

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mosses was 2 species. Thus, the total number of moss species as a result of the transformation of plant communities decreased by more than two times; at specific most disturbed locations, the species diversity of mosses decreased by three times. Moss species that have disappeared from the studied communities—*Climacium dendroides* (Hedw.) F. Weber & D. Mohr, *Dicranum majus* Turner, and others—are more demanding on microhabitat conditions. In particular, they need shading, which is absent in the communities at the initial stages of post-cutting succession. One moss species (*Ptilium crista-castrensis*), which was absent at the control, appeared in the felled area.

In the ruts, a strong degree of disturbance of the original vegetation was observed, most of which was mechanically destroyed. The shrub layer was represented by single rosehip plants (*Rosa acicularis* Lindl.) and mountain ash (Sorbus aucuparia L.). The projective cover of the herb-shrub layer was about 3%; the projective cover of of mosses and lichens, up to 5%. The average α -diversity of vascular plants was reduced to two species. Dominant species of the original communities, which retain their abundance in residual stands, are absent in the ruts. Under such conditions, in the first year of succession, loosestrife (Lysimachia europaea (L.) U.Manns & Anderb.), goldenrod (Solidago virgaurea virgaurea L.), globular sedge (Carex globularis L.) become dominant plants; among mosses, Sphagnum angustifolium predominates.

Ruts with varying degrees of disturbance (3 and 10 forwarder passages) differ significantly in the main parameters of the lower vegetation layers. The average number of vascular plant species (α -diversity) in a rut after three passages is 3 species (1–5 species on specific sites); after ten passages, it is 2 species (0–2 species on specific sites). The moss–lichen layer in the ruts is completely absent after 10 passages; after three passages do not contain any plants in the first year of the restoration succession.

In general, according to the results of vegetation cover studies, it can be noted that on different technological elements of felling areas (residual plots, ruts on trails), different degrees of disturbance of the vegetation cover can be observed. The degree of vegetation disturbance depends on the level of technological load in the course of felling operations.

Restoration of the main tree species on different elements of felled areas in the first year. The composition of regrowth in clearings is 54A44B1S1P. The highest occurrence is observed for aspen, both in residual forest stands and on skidding trails (t = 0.45-0.65); the lowest occurrence is typical of conifers (t = 0-0.05). After three passes of the forwarder along the trail, higher values of the index in the ruts are noted for aspen (t = 0.71). On trails after ten passes, birch and aspen were observed in equal proportions (t = 0.22) (Table 2), but mostly of seed origin. This trend is asso-

Table 1. Characteristics of the lower tiers of vegetation of t	ne studied techn	logenic element	s of felling area	
Index	Control	R	3P	10P
The total density of the undergrowth, in fractions of 1	0.2	0.1	<0.1	<0.1
Total projective cover of herb–shrub layer, $\%$	80	20	1-3	0-1
Total projective cover of the moss–lichen layer, $\%$	80	60	1-5	0
Und	ergrowth	1	I	1
Rosa acicularis	2	9	8	10
Salix caprea	+	1	_	_
Sorbus aucuparia	8	+	2	_
Herb–	shrub layer	1	I	1
Chamaenerion angustifolium	1	1	—	-
Equisetum sylvaticum	2	1	_	_
Gymnocarpium dryopteris	2	1	_	_
Blueberry blueberry	8	5	_	_
Calamagrostis obtuse	1	1	3	_
Scarce globular	2	4	5	_
Deschampsia flexible	3	3	2	_
Maianthemum bifolium	4	1	2	_
Blueberry vines	2	5	1	_
Melampyrus forest	1	2	5	3
Solidar wood	1	2	4	4
Triennial europaea	3	1	6	7
Luzula hairy	1	2	_	3
Bush stony	3	2	_	4
Moss–lichen layer	1	1	I	1
Polytrichum common	4	5	_	-
Aulacomnium swamp	1	3	_	_
Pleurisy to be scratched	4	4	5	-
Hylocomium shining	7	5	5	-
Sphagnum angustifolium	4	5	6	-

 Table 1. Characteristics of the lower tiers of vegetation of the studied technogenic elements of felling area

Control—initial forest of the background area; R—residual forest plots remaining after felling; 3P—skidding trail after three forwarder passes; 10P—skidding trails after ten forwarder passes/. For the undergrowth, the composition is given (from 10 units). The abundance ranks of species of the herb—shrub and moss—lichen stages are given according to the Ipatov scale [19]. Species noted only in the control plot: *Carex cespitosa, Dicranum majus, Geranium sylvaticum, Hieracium laevigatum, Juniperus communis, Platanthera bifolia.* Species noted only in the residual forest plot: *Leontodon autumnalis, Linnaea borealis, Oxalis acetosella, Rhytidiadelphus subpinnatus.* Dashes denote the absence of species.

ciated with the disturbance of forest litter and its mixing with the upper eluvial soil horizons, resulting in better fixation and germination of tree seeds in the mineral soil. However, with an increase in the depth of the ruts and their waterlogging, the young growth disappears.

The density and species composition of young growth in the clearing of coniferous-deciduous stands attest to abundant regrowth of deciduous species of birch and aspen. Their number is 11 and 13 thousand units/ha, respectively. Seedlings of spruce and pine are single. Such a weak renewal of spruce and pine is associated with a low fruiting score of coniferous trees in the felling in the previous year. The young growth occurrence index (*t*) is uneven regardless of the technological element of felling area (3P, 10P, 10P). Thus, throughout the clearing, the highest index is noted on the trails (t = 0.7), while in the areas subjected to leveling, it is zero. The established accounting plots showed a complete absence of young growth on 10P plots as a result of leveling and removal of the upper horizons.

Changes in soil morphology. A reference soil profile was laid in the central part of the felling area (Fig. 3). The pre-cutting microtopography of this plot on the top of the moraine ridge is typical of forest ecosystems: near-stem microhighs, abundant stumps and dead-wood of different stages of decomposition. The soils of



Fig. 3. General view of the studied plots and soil profiles: IF—initial forest (control); 3P—skidding trails after three forwarder passes; 10P—skidding trail after ten forwarder passes, 10Pl—skidding trail after ten forwarder passes and surface leveling.

the initial forest (IF) are characterized by the presence of forest litter with three subhorizons of different degrees of decomposition of plant residues (O(L),O(F), O(H)) [6]. Under the litter, a whitish (2.5Y 5/3-10 YR 6/3) eluvial horizon EL is formed, which is represented by structureless or weak platy loam. Gravelly material is abundant in this horizon. The transition to the subeluvial BEL horizon of a heavier texture is gradual. The BEL horizon is dark brown to light gray (7.5YR 4/4), well structured, and penetrated by vertical tongues of the eluvial horizon with coarser loamy sandy material. A reddish brown (7.5Y 4/4) silt loamy BT horizon with a multi-order structure typical of podzolic soils and with abundant cutans and skeletans is seen under the eluvial layer. This soil is classified as a typical podzolic soil (Retisol).

Pit 3P was laid in the central part of the trail with three forwarder passes. There is no ground cover; there are many branches and needles in the upper part of the litter, but no mixing of the upper horizons is observed. Visual overcompaction of the soil and additional input of organic matter into the upper mineral horizons have been noted. The soil profile has the following horizonation: O(L) (0-2 cm) - O (F + H) (2-5 cm) - EL1(5-15 cm)-EL2 (15-25 cm)-BEL (25-35 cm)-BT1 (35-50 cm). The litter layer is subdivided into two subhorizons according to the degree of decomposition of plant residue represented by needles, branches, remains of mosses and shrubs and by well-decomposed plant litter in the lower part of the horizon. The upper mineral horizon EL1 is structureless whitish loamy sand (2.5Y 5/2) with abundant rounded gravels.

Species	Density of regrowth trees/hs	Index occurrence (<i>t</i>)					
species	Density of regiowin, trees/its	3P	10P	10P1	R*		
В	10714	_	0.22	_	0.15		
А	13214	0.71	0.22	—	0.45		
F	179	—	—	—	—		
Р	179	—	—	0.08	—		
Total	24286	0.71	0.33	—	0.50		

Table 2. Characteristics of the subsequent natural forest restoration and the index of occurrence of regrowth in the felling areas of the first year

A-aspen, B-birch, F-spruce, P-pine. Dash-not found. *R-residual forest plot

The EL2 horizon is lighter (2.5Y 6/2) and denser; it has a sand loamy texture. The underlying mineral BEL and BT horizons have not been subjected to mechanical disturbances and are similar to the horizons of the background area. This soil is also classified as a typical podzolic soil.

Pit 10P was laid on a trail after ten forwarder passes that left a deep rut. There is no litter in the rut, but there are many branches, needles and logging residues on the surface. The soil profile has the following horizons: TURcwd² (0–15 cm)–EL (15–20 cm)–BEL (20-30 cm)-BT (30-50 cm). The upper turbated horizon TURcwd is a gray mineral horizon with an admixture of branches, needles, cones, and occasional gravels. The underlying eluvial horizon corresponds to that in the background soil, but is more compacted, with elements of platy and angular blocky (nutty) structure. The subeluvial BEL and textural BT horizons are almost identical to those in the initial native soil.. However, some overcompaction of the soil material is observed in the middle-profile mineral horizons. This soil was classified as a turbated soil with plant detritus (detrital turbozem).

Pit 10Pl was laid on the trail subjected to ten forwarder passes with subsequent surface leveling. The soil surface is uneven, with numerous microlows filled with water in the summer. The upper horizons are turbated; the restoration of vegetation is slow. There are single branches and remains of the organic horizon on the surface. The soil horizonation is as follows: TUR (0-10 cm)-BEL (10-20 cm)-BT (20-50 cm). There is no organic horizon; as a result of the leveling, a strongly turbated (TUR) horizon is formed with a partially preserved structure of the EL and BEL horizons. In contrast to profile 10P, there are significantly fewer logging residues and plant litter on the surface. The BEL horizon forming below is brown (7.5YR 4/3), with white tongues; it is dense. The BT horizon is represented by brown (7.5YR 4/3) heavy loam. The entire soil profile is cemented, probably due to desiccation/wetting cycles. This soil was classified as a turbozem.

Rut depth. Wheeled heavy vehicles passing along the trail break through the soil to a depth of 0-41 cm leaving deep ruts (Fig. 4). On trails with three forwarder passes, the depth of the ruts varied from 8 to 13 cm. Ruts are the deepest in better moistened places. After ten passes, the depth of the ruts increases (0 to 66 cm with the average depths of 23-35 cm). Thus, the depth of the ruts increases by two-four times after ten passes in comparison with that after three passes of heavy wheeled forwarder even in the case of significant soil tolerance towards mechanical loads.

An analysis of the variation indicators made it possible to establish that, on average, the depth of the ruts after three passes is 11 ± 8 cm. The variation coefficient of 79% in this case indicates the heterogeneity of the obtained indicators in accordance with the normal distribution (Kolmogorov–Smirnov criterion (*D*) is 0.149, at p < 0.01; the Shapiro–Wilk test W = 0.8654 at p = 0.0009). For ten-pass ruts, their average depth is 27 ± 12 cm with a coefficient of variation of 45%; thus, the depth of the ruts becomes more even. The observed sample corresponds to the normal distribution law (criterion D = 0.05711 at p < 0.02, criterion W = 0.98633 at p = 0.0009).

Soil density. A study of the density of the upper genetic horizons after the experiment with three and ten forwarder passes has been specially conducted. In the residual forest area, the soil bulk density is close to that in the control: 0.09 g/cm_3 in the litter horizon and 1.46 to 2.09 g/cm³ in the mineral horizons (Fig. 5).

Some changes in the bulk density of genetic horizons take place in the soils of trails. After three forwarder passes, bulk density of the litter increases up to 0.13 g/cm^3 and the density of the upper eluvial horizon is up to 1.70 g/cm^3 . Bulk density of the lower horizon is close to that in the control (undisturbed plot). After ten forwarder passes, the litter horizon virtually disappears, and bulk density of the upper mineral horizon decreases to 1.18 g/cm^3 because of its mixing with litter. However, bulk density of the middle-profile EL2 horizon increases to 1.92 g/cm³ because of high mechanical loads.. For the soil of plot 10Pl, an increase in the bulk density of the turbated horizon up to 1.67 g/cm^3 was found; its bulk density is close to that of the upper eluvial horizon after three forwarder passes. The lower mineral horizons are less compact $(1.63 - 1.71 \text{ g/cm}^3)$.

At the same time. statistically significant differences in the density of the upper horizons of the soils of the trails depending on the number of passes of wheeled vehicles have not been found. However, it should be noted that there is a tendency towards a decrease in the soil density on the trails after ten forwarder passes, which is probably associated with loosening and mixing of the mineral horizon with the litter layer.

Changes in the physicochemical properties. The initial soil (IS) developed from sandy loam/silt loam material. The content of physical clay (<0.01 mm) particles varies from 19 to 31%. A heavier texture in the lower mineral horizons is clearly manifested. The content of the clay fraction is low (8–9%) in the upper mineral horizons and increases to 23% in the BT horizon. The clay differentiation coefficient in the soil profile is 2.7.

The initial soil is acid to slightly acid $(pH_{water} 4.3 - 6.1)$. The most acidic is the litter; in mineral horizons, pH approaches neutral values. The distribution of carbon and nitrogen along the profile is regressively accumulative with the highest content in the litter (34.4–

² The cwd symbol denotes the presence of coarse woody residues (from English coarse wood debris). The use of this index in turbated horizons was described in detail by us earlier [14].



Fig. 4. Depths of ruts on skidding trails (1–6) after (a) three and (b) ten forwarder passes. drags with three (a) and ten (b) passes.



Fig. 5. Bulk density of soil horizons in the studied pits. IF—initial soil, R—soil of the residual forest plot, 3P—soil of the skidding trail after three forwarder passes, 10P—soil of the skidding trail after ten forwarder passes, 10PL—soil of the skidding trail after 10 forwarder passes and surface leveling. Mean \pm rms deviation (n = 5).

44.5%) and the lowest content in the mineral horizons (0.1-0.45%). The organic matter of the litter is characterized by a wide C/N ratio (29 to 37). The content of available phosphorus in the initial soil varies from 100 to 1500 mg/kg with a maximum in litter subhorizons O(F) and O(F + H). The mineral horizons contain 6–18 times less phosphorus. The minimum content of available phosphorus is in the eluvial horizons, which is typical for podzolic soils.

The distribution of dithionite- and oxalate-soluble forms of iron and aluminum in mineral horizons has an eluvial—illuvial distribution along the profile. There is a removal of iron and aluminum from the upper mineral horizons and their accumulation in the middle part of the profile with further decrease in their content in the lower mineral horizons. Physicochemical properties of the initial soil generally correspond to the properties of podzols in the studied region [35].

The accumulation of oxalate-soluble forms of iron to some extent reflects the degree of soil hydromorphism. It is believed that the values of the Schwertmann coefficient (Ksh) allow one to obtain a quantitative expression for the degree of soil hydromorphism [1, 9, 20]. The values of Ksh varied from 0.4 to 0.6. High values of the Schwertmann coefficient were found in the EL and BEL horizons, where some moisture stagnation takes place (Ksh = 0.6). Increased hydromorphism is observed in soils on flat surfaces because of the absence of lateral runoff.

For the soil of the residual plot (P), a decrease in the content of both dithionite- and oxalate-soluble forms of iron in comparison with the control plot has been found. It is likely that an increase in the mobility of these forms of iron is associated with an increase in the water content of the upper genetic soil horizons within the residual area after felling. The aluminum content in the upper part of the illuvial horizon decreases by a factor of three; at a depth of 20–45 cm, it increases by two times. The carbon and nitrogen contents gain their maximums (34.5-44.8 and 1.11-1.90%, respectively) in the organic horizon and decrease to 0.112-0.82% carbon and 0.018-0.033% nitrogen in the mineral horizons. In the soil of the residual plot, no changes were found in the contents of carbon and nitrogen in comparison with the initial soil. The available phosphorus content somewhat increased (up to 1700-1900 mg/kg compared to 1400–1500 mg/kg in the initial soil) in the organic horizon; mineral horizons of both soils were characterized by close values of the available phosphorus content (46-150 mg/kg).

According to the chemical indicators for the soils of trails, some of them were close to those in the initial soil, whereas others differed significantly. The acidity indices in the soils of the trails remained similar to those in the initial soil (Table 3); pH_{water} in the soil P3 was 4.4 to 5.8; in the soil P10, it varied from 4.7 to 5.9; in the soil P101, from 5.1 to 5.5. The most acidic were

the organic subhorizon O(F + H) (pH 4.4) and the upper eluvial horizon (pH 4.7) in the soil of the trail 3P. There was some increase in the acidity of the upper turbated TUR horizon in the soil 10P (pH 4.7), which was probably associated with an increase in the number of branches, needles, and logging residues on the soil surface.

Analysis of particle-size distribution data (Table 4) made it possible to reveal some increase in the content of coarse and medium silt fractions in the mineral horizons of the soils of the trails in comparison with the initial soil. The content of coarse silt varied from 17 to 30%; the content of medium, from 2 to 10%, which was 1.1-1.6 times higher than in the initial soil of background area (control). In addition, an increase in the clay content in the middle and lower mineral horizons of the soils of the trails by 1.2-5.0 times was found. The content of the clay fraction in the soil of plot 3P varied from 13 to 44%; in the soil of plot 10P, from 19 to 46%. The maximum increase in the clay content was in the soil of plot 10Pl (20 to 60%). The distribution of the physical clay fraction (<0.01 mm) had a clear eluvial pattern with an increase in the lower mineral horizons. Removal of the litter and, in some cases, eluvial and subeluvial horizons exposed heaviertextured underlying horizons. It can be stated that the present-day upper horizons of the soils of the trails are somewhat heavier in texture than the initial soils. This may be due to the spatial heterogeneity of soil-forming rocks. Also, removal of the upper mineral horizons can contribute to the appearance of heavier-textured lower horizons on the surface.

The contents of carbon and nitrogen in the soils of the trails are characterized by significant changes in comparison with the initial soil: the upper mineral horizons become enriched in carbon and nitrogen. In the soil of plot 3P, the content of carbon and nitrogen in the litter horizon was close to the initial values: 42.5-47.0% C and 1.24-1.25% N; in the mineral horizons, the carbon content varied from 0.14 to 0.65%, and the nitrogen content varied from 0.017-0.049%, which corresponded to the initial values. The content of carbon in the turbated horizon (plots 10P and 10Pl) ranged from 0.32 to 2.2%; the nitrogen content, from 0.031 to 0.112%. In the lower mineral horizons, the values were close to the initial contents of these elements. The maximum content of carbon (2.2%) and nitrogen (0.112%) in the mineral horizons was found in the soil of plot 10P, which was due to the mixing of mineral material with the organic matter of the litter.

The distribution of iron and aluminum in the soil profiles displayed the eluvial–illuvial patterns with the removal from eluvial horizons and accumulation in the middle-profile horizons. The content of dithion-ite-soluble iron in the soils of the trails was slightly higher than that in the initial soil and varied from 0.25 to 1.21%. The content of oxalate-soluble iron was

Ľ	lable 3.	Physical and	l chemical proj	perties of:	soils								
EUR	Soil	Horizon	Denth cm	Į	Н	C	Z	NC	$\mathrm{F}e_2\mathrm{O}_{3\mathrm{dith}}$	$\mathrm{Fe}_{2}\mathrm{O}_{3\mathrm{ox}}$	Al_2O_{3ox}	Keh	P (total),
ASIA	profile	110711011	Doput, cui	H_2O	KCI	5	20			%		IICAI	mg kg ⁻¹
I AN S		0(T)	0 - 1	5.3	5.0	42.9 ± 1.5	1.73 ± 0.19	29		Not	det.		1400 ± 400
OIL	_	O(F)	14	4.5	3.6	44.5 ± 1.6	1.72 ± 0.19	30		Not	det.		1500 ± 500
SCI	_	(H)O	45	4.3	3.5	34.4 ± 1.2	1.10 ± 0.12	36		Not	det.		1400 ± 400
- IEN	μ	EL1	5-20	5.0	3.9	0.45 ± 0.10	0.037 ± 0.011	14	0.54	0.23 ± 0.01	0.15 ± 0.04	0.4	100 ± 30
- CE	Ľ	EL2	20-45	5.7	4.0	0.16 ± 0.04	0.021 ± 0.006	6	0.72	0.42 ± 0.01	0.13 ± 0.03	0.6	160 ± 50
V	_	BEL	45-65	5.8	4.1	0.21 ± 0.05	0.023 ± 0.007	П	0.82	0.51 ± 0.01	0.15 ± 0.04	0.6	180 ± 50
ol. 5:	_	VT1	65-85	6.0	4.0	0.12 ± 0.03	0.024 ± 0.007	9	0.72	0.28 ± 0.01	0.13 ± 0.03	0.4	200 ± 60
5	_	VT2	85-110	6.1	3.9	0.12 ± 0.03	0.025 ± 0.007	9	0.80	0.29 ± 0.01	0.15 ± 0.04	0.4	220 ± 70
I No.		0(T)	0 - 1	5.4	4.4	44.8 ± 1.6	1.90 ± 0.21	28		Not	det.		1900 ± 600
11	_	O(F)	14	4.6	3.6	44.4 ± 1.6	1.60 ± 0.18	32		Not	det.		1800 ± 500
⊢ 202	_	0(H)	45	4.2	3.2	40.0 ± 1.4	1.22 ± 0.13	38		Not	det.		1700 ± 500
-		EL1	5-20	4.6	3.8	0.31 ± 0.07	0.025 ± 0.007	14	0.05	0.0032 ± 0.08	0.054 ± 0.013	0.6	46 ± 14
	_	EL2	20 - 40	5.0	4.2	0.54 ± 0.12	0.033 ± 0.010	19	0.12	0.066 ± 0.016	0.272 ± 0.06	0.5	130 ± 40
	_	BEL	40-60	5.5	3.7	0.112 ± 0.026	0.019 ± 0.006	7	0.72	0.45 ± 0.108	0.133 ± 0.03	0.6	150 ± 40
I		0(T)	0-2	5.1	4.5	47.0 ± 1.6	1.24 ± 0.14	44		Not	det.		1200 ± 400
	_	O(F + H)	2-5	4.4	3.4	42.5 ± 1.5	1.25 ± 0.14	40		Not	det.		1500 ± 400
6	D	EL1	5-15	4.7	3.8	0.65 ± 0.15	0.049 ± 0.010	15	0.33	0.28 ± 0.07	0.15 ± 0.03	0.8	160 ± 50
1	1	EL2	15-25	5.4	3.9	0.15 ± 0.03	0.017 ± 0.005	10	0.38	0.28 ± 0.04	0.112 ± 0.027	0.7	180 ± 50
	_	BEL	25-35	5.7	3.6	0.14 ± 0.03	0.019 ± 0.006	6	0.80	0.37 ± 0.09	0.14 ± 0.03	0.5	190 ± 60
	_	BT	35-50	5.8	3.7	0.16 ± 0.04	0.023 ± 0.007	8	1.01	0.35 ± 0.08	0.16 ± 0.04	0.3	240 ± 70
I		TURcwd	0-15	4.7	3.6	2.2 ± 0.3	0.112 ± 0.022	23	0.25	0.16 ± 0.04	0.18 ± 0.04	0.6	220 ± 70
	dU	THE	15 - 20	5.3	3.9	0.27 ± 0.06	0.026 ± 0.008	12	0.31	0.18 ± 0.04	0.115 ± 0.028	0.6	150 ± 40
-	10	BEL	20-30	5.7	3.5	0.18 ± 0.04	0.026 ± 0.008	8	1.02	0.46 ± 0.07	0.193 ± 0.046	0.5	240 ± 70
ļ		BT	30-50	5.9	3.6	0.15 ± 0.03	0.026 ± 0.008	7	1.15	0.34 ± 0.06	0.15 ± 0.036	0.3	320 ± 100
	_	TUR	0 - 10	5.1	3.8	0.32 ± 0.07	0.031 ± 0.009	12	0.59	0.35 ± 0.08	0.141 ± 0.034	0.6	160 ± 50
1	IOPI	BEL	10 - 20	5.5	3.4	0.25 ± 0.06	0.038 ± 0.011	8	1.21	0.42 ± 0.06	0.28 ± 0.07	0.3	250 ± 70
	_	BT	20 - 50	5.7	3.4	0.17 ± 0.04	0.035 ± 0.010	9	1.15	0.31 ± 0.07	0.212 ± 0.05	0.3	330 ± 100
¥	<sh−schv< td=""><td>vertmann coe</td><td>fficient, the ration</td><td>o of oxalate</td><td>e-soluble to</td><td>dithionite-solub.</td><td>le forms of iron.</td><td></td><td></td><td></td><td></td><td></td><td></td></sh−schv<>	vertmann coe	fficient, the ration	o of oxalate	e-soluble to	dithionite-solub.	le forms of iron.						

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Soil profile			Size of particles, mm; particle content, %							
			sand		silt				sum of particles	
	Horizon	Depth, cm	coarse + medium	fine	coarse	medium	fine	clay	>0.01 mm	<0.01 mm
			1-0.25	0.25-0.05	0.05-0.01	0.01-0.005	0.005-0.001	< 0.001		
	EL1	5-20	35	30	16	5	5	9	81	19
	EL2	20-45	19	31	22	7	12	9	72	28
IF	BEL	45-65	31	35	14	1	11	8	80	20
	VT1	65-85	20	38	15	0	5	22	73	27
	VT2	85-110	16	38	15	1	7	23	69	31
	EL1	15-15	49	19	18	5	2	7	86	14
210	EL2	15-25	20	29	23	6	13	9	72	28
3P	BEL	25-35	14	32	21	5	13	15	67	33
	BT	35-50	10	30	16	6	11	27	56	44
	TUR cwd	0-15	31	29	18	6	7	9	78	22
10 D	THE	15-20	32	26	23	6	6	7	81	19
101	BEL	20-30	13	25	18	6	15	23	56	44
	BT	30-50	13	23	19	8	11	28	54	46
10P1	TRIP	0-10	18	29	25	9	13	5	73	27
	BEL	10-20	8	13	19	5	14	41	40	60
	BT	20-50	8	17	18	6	13	40	42	58

Table 4. Particle-size distribution data

close to that in the initial soil (0.16-0.46%). The soils of the trails are somewhat wetter than the initial soils, in which the Schwertmann coefficient is 0.3-0.6. In the soils of the trails, it varies from 0.3 to 0.8 with maximum values (0.6-0.8) typical of the upper eluvial and turbated horizons. The content of oxalate-soluble aluminum is weakly differentiated along the soil profiles on the trails.

The distribution of total phosphorus in the profile of physically disturbed soils has an accumulative character with an increase in the content in the lower mineral horizons, which is consistent with the results for the initial soils. The content of phosphorus on plot 3P in the litter layer is 1000-1200 mg/kg (the same as in the initial litter horizon). The main differences concern the mineral horizons. All the soils of trails are characterized by a general increase in the available phosphorus content of the mineral horizon. On plot 3P, it varied from 160 to 220 mg/kg; on plot 10P, from 150 to -320 mg/kg; on plot 10Pl, from 160 to 330 mg/kg. An important feature of the soils of the trails is an increase in the content of phosphorus in the upper eluvial and turbated horizons from 100 mg/kg in the background soil to 160–220 mg/kg in the soils of the trails.

CONCLUSIONS

In the course of the field experiment, conditions with a different number of forwarder passes were simulated, as well as activities related to the leveling of ruts on the skidding trails. It was found that the number of passes of heavy wheeled machines is the decisive factor in the transformation of soils and vegetation on the trails. Under the same conditions and load of the forwarder, ruts of different depths with varying degrees of disturbance appear on the trails after 3 and 10 forwarder passes.

The formation of ruts with a depth of 11 ± 3 cm is observed on the trails after three forwarder passes. The depth of the ruts after ten passes can reach 66 cm with average values equal to 27 ± 4 cm. The leveling of the trails with ruts after ten passes leads to the complete destruction of the vegetation and the most significant transformation of the natural composition of the upper soil horizons over a larger area. A statistically significant increase in the density of the upper mineral horizon in the soil of the trail after three passes of forwarder was determined.

In the soil subjected to ten forwarder passes, bulk density of the upper mineral horizons decreases because of the admixture of the remains of surface litter into it. At the same time, the underlying middleprofile mineral horizons become more compacted. The upper horizons of the soil of the trail with leveling of the surface by an excavator, a statistically significant increase in the bulk density of the upper mineral horizon was noted; it took place because of the partial

removal of the upper horizon and appearance of the heavier underlying horizons on the surface.

The change in soils and vegetation in the first year after the impact of machinery with different intensity was assessed. It can be assumed that further restoration and change of the ecosystem components under consideration will occur at different rates. These objects can be used for further monitoring of the success of reforestation in dependence on the particular forest management activities.

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CONFLICT OF INTERESTS

The authors declare that they have no conflict of interest.

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