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Original article

RECOVERY OF THE SOIL AND PLANT COVER IN THE SKID TRAILS AFTER THINNING IN MYRTILLUS TYPE FORESTS OF THE NORTHERN TAIGA

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Disturbance of soil and plant cover caused by logging operations results in various damages and can give rise to soil degradation and plant succession. We studied the recovery of soil and plant cover in the damaged skid trails of different periods after two-stage thinning of the Piceeta myrtillosum type forest. Thinning was conducted in 1973 and in 2002. The in-situ soil cover is represented by podzolic light loamy soil overlying heavy moraine loam. Tree-felling was carried out using a chainsaw, and tree-length skidding was carried out using a TDT-55 cable skidder. We studied the species composition and species ratios for different ecological groups of grass-shrub and moss layers, forest litter formation and soil properties and found higher plant species diversity in the skid trails and dissemination of the wetland group species, with Sphagnum mosses being indicators of swamping. These features provide thicker forest litter in the skid trails rather than in cut strips in the course of plant cover restoration. Due to swamping, the thickness of the forest litter increases in the process of succession. In the course of the natural recovery of the skid trails, the most significant changes of the soil were observed at the depth of 0–10 cm. The bulk density in the upper layer of the soil significantly reduces to 0.85–0.98 g.cm^{-3}, when that of the cut strips is 1.19 g.cm^{-3}. This results in organogenic substances associated with detritus decomposition and peat litter formation entering into the mineral part of the soil. At the depth of 10–20 cm, compaction caused by machinery passage is noted both 17 years and 46 years after thinning. In the myrtillosum *forest type, the recovery of plant and soil cover typical of Piceeta myrtillosum in the conditions of the northern taiga subzone, was not observed for 50 years.*

Keywords: *thinning; skid trails; cutting strips; soil disturbance; soil physical properties*

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Научная статья

ВОССТАНОВЛЕНИЕ ПОЧВЕННОГО И РАСТИТЕЛЬНОГО ПОКРОВА НА ВОЛОКАХ ПОСЛЕ РУБОК УХОДА В ЧЕРНИЧНОМ ТИПЕ ЛЕСА СЕВЕРНОЙ ТАЙГИ

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Нарушение почвенного и растительного покровов при лесозаготовительных работах вызывает повреждения разных типов и может привести к деградации почв и к сукцессиям растительности. Изучили процесс восстановления почвенного и растительного покровов на поврежденных лесозаготовительной техникой волоках разного периода при проведении двухприемных рубок ухода в ельнике черничном северной подзоны тайги (Архангельская область, Россия). Двухприемные рубки проводились в 1973 г. и в 2002 г. Почвенный покров на участке представлен подзолистой легкосуглинистой почвой, сформированной на тяжелом моренном суглинке. Рубку проводили бензопилой, трелевку хлыстами гусеничным трактором ТДТ-55. Изучили видовой состав и соотношение видов разных экологических групп травяно-кустарничкового и мохово-лишайникового ярусов, формирование лесной подстилки и свойства почвенных горизонтов. Установлено повышение видового разнообразия растительности на волоках, появление видов водно-болотной группы, в том числе Сфагновых мхов, которые являются индикаторами заболачивания. Это ведет к увеличению мощности лесной подстилки на волоках по мере восстановления растительного покрова по сравнению с пасекой. Мощность лесной подстилки из-за оторфянивания растет в процессе сукцессии. При естественном зарастании волоков после рубки наиболее значимые изменения происходят *в почве на глубине 0-10 см. Плотность сложения в верхнем слое почвы заметно снижается до 0,85-0,98 г/см^3, по сравнению с пасекой (1,19 г/см^3). Это связано с поступлением в минеральную часть почвы органогенных веществ, связанных с разложением детрита и формированием торфяной подстилки. На глубине 10-20 см уплотнение, вызванное проездами техники, отмечается и через 17 лет после рубки, и через 46 лет. За 50 лет в черничном типе леса в условиях подзоны северной тайги восстановление растительного и почвенного покровов, характерного для данных условий не происходит.*

Ключевые слова: *рубки ухода; трелевочные волока; пасеки; нарушение почвы; физические свойства почвы*

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Introduction

Issues of compliance with forest ecology, especially during logging operations, are of increasing concern to scientists. Particular attention has been paid to the damage to the soil cover, which is one of the most important factors of ecosystem productivity and forest regeneration [24]. Disturbance of the soil cover during logging operations is primarily due to the damage of various types caused by machinery operations, which gives rise to soil degradation [25]. The degree of soil damage depends on the habitat conditions and the machinery and wood harvesting systems used [27; 33] and is more noticeable in the upper organogenic horizons than in the mineral layers [2].

Issues relating to the possibility and duration of damaged soil and plant cover restoration are also important. Undoubtedly, the recovery of the soil and plant cover after damage resulting from logging machinery operations is associated with the duration of the period after felling [20; 28; 30; 32; 35]; however, it also depends on growing conditions, soil properties and the impacted depth [20; 23]. Plant cover recovery and soil cover recovery within damaged areas are interconnected. Dispersal and successful plant and tree growth depends on soil properties [26; 38]; however, the rates of the regenerative successions of plants and soils may be different and depend on changes in the physical properties, as well as in the chemical and biological properties of soils, that occur as a result of the logging machinery impact [25; 40].

For the development of low-impact (nature-friendly) wood harvesting systems and new logging machines, and for the revision of technological processes, it is important to obtain information on the impact of logging in different soil and weather conditions and when using different operational technologies both for clear-cut and thinning areas.

The purpose of this research is to study the soil and plant cover recovery in the skid trails of different periods damaged by skidders during two-stage thinning of the *Piceeta myrtillosum* type forests in the northern taiga subzone to find solutions to problems arising from the duration of the recovery period.

The hypothesis of the study is as follows. Under the impact of the relatively light machinery used in thinning areas of a *Piceeta myrtillosum* type forest of the northern taiga subzone: 1) the disturbances of the plant and soil cover in the skid trails covered with felling residue will have a long recovery period , and 2) these changes will be accompanied by the growth of moisture-loving plants and the development of swamping, even without the formation of deep ruts.

Material and Methods

The research was conducted in 2019–2020 at the thinning area in the Ust-Dvinsky forest district in the Arkhangelsk region (northern taiga subzone). The plots are located by the following coordinates: 64°46’N 40°94’E. Two-stage thinning was carried out in 1973 and in 2002 in a mixed forest stand with the following composition: 60% spruce (*Picea abies* /L./ H.Karst); 30% pine (*Pinus sylvestris* L.); 10% birch (*Betula pendula* Roth.) and a single aspen (*Populus tremula* L.). The soil cover in the site is podzolic sandy loamy soil, which is typical of *myrtillosum* spruce forests of the northern taiga, underlaid by heavy moraine loam.

In the forest stand, primary skid trails were cut for passage of a skidder of 4 m width, with 30 m space on the first stage and shifting 10 m towards the cutting strip on the second stage. For the wood harvesting system, the tree-length system was used. Tree felling was carried out using a chainsaw, and trunk skidding was carried out using a TDT-55 tracked skidder. Felling residues were laid on the skid trails; however, due to the low intensity of thinning (38.9 m^3/ha^{-1}), the felling residues covered only 32% of the skid trail area [1], which undoubtedly impacted the soil cover damage.

This survey was conducted in three cut strips and skid trails in *Piceeta myrtillosum* forests. The natural tree regeneration and plant cover were assessed according to generally accepted methods. To estimate the undergrowth, five plots of 2 × 5 m size were laid in each cut strip and each skid trail; the obtained data was collected by species and reduced to an area of 1 ha. The undergrowth was estimated using three size categories: small (height up to 0.5 m), medium (height of 0.51 m to 1.5 m), and large (height over 1.51 m).

The geobotanical assessment of the plant cover within the study plots was performed using traditional methods [15]. An ecological and biological assessment of the plant cover was conducted using modern methodological approaches [7; 15], and total projective coverage of the grass-shrub and moss layers, along with the projective coverage for each species were determined. The identification of plant species was conducted using standard determinants for the flora of the north-east of the European part of Russia taken from an atlas of plant and lichen species and an illustrated guide to plant identification [11]. The names of vascular and non-vascular plants were given according to the international database [39]. Ecological analysis was used to study the differentiation of the grass-shrub and moss layers [11]. The distribution of the moss layer species by ecological-cenotic groups was carried out according to Kireev et al [8], and a comparative floral assessment was conducted using the Shannon [36] and Jacquard [12] indices.

To study the structure and types of soil damage in the skid trails, along the skidder tracks ("the edge of the skid trail") between them ("the centre of the skid trail") and in the cut strips – the upper soil horizons were opened to a depth of at least 40 cm. It is only at this depth that soil damage from logging can be diagnosed [4]. The soil was opened with 2 m space. The total number of test points was 180.

Each pit was described, in accordance with Shishov et al. [9], in terms of its horizons detection, thickness measurement and genetic signs (gleying, swamping, etc.). Undisturbed samples of forest litter and soil were taken from depths of 0–10 cm and 10–20 cm to determine their physical properties. The number of samples of forest litter was as follows: 28 for the edge of the skid trails (1973), 16 for the centre of the skid trails (1973), 28 for the edge of the skid trails (2002), 16 for the centre of the skid trails (2002) and 16 for the cut strips. The same number of soil samples were taken at depths of 0–10 cm and 10–20 cm.

The bulk density was calculated by Formula 1 [31]:

$$D_b = \frac{W_D}{V}, \tag{1}$$

Where: D_b is bulk density, g·cm^{-3}; W_D is the dry soil weight; V is cylinder or template frame volume, cm^3.

The density of the solid phase was determined pycnometrically for each soil sample in 2 repetitions. The bulk density and the density of the solid phase were used to calculate the total porosity, which was determined by the following Formula 2:

$$\varphi = \left(1 - \frac{D_b}{D_d}\right) \cdot 100, \qquad (2)$$

Where: φ is total porosity, %; D_d is density of the solid phase, g·cm^{-3}.

The mean value, standard error, minimum and maximum values and coefficient of variability were calculated for the physical properties of the forest litter and the soil. To establish the differences between the studied physical properties, a nonparametric one-way analysis of variance (ANOVA) was used. When rejecting the null hypothesis, subsequent multiple comparisons were used to establish the differences between the groups (the Kruskal–Wallis test). All statistical analyses were performed at a 0.05 significance level, and data processing and analysis conducted out using STATISTICA version 12.

Results

The natural renewal of trees in the skid trails of different ages resulting from thinning differs from that in the cut strips (Figure 1). In the cut strips, the common composition of undergrowth is 60% spruce, 37% aspen and 3% birch, with a total number of 5.6 thousand plants per hectare.

Fig. 1. The amount of undergrowth at the study sites
(thousands of individuals per hectare)

The undergrowth in the 1973 skid trails (46 years after thinning) and the 2002 skid trails (17 years after thinning) differs, which could be a result of the coincidence or non-coincidence of the felling years and seed years, primarily for conifers. In the 1973 skid trails, the undergrowth composition is 50% spruce, 43% birch, 5% aspen and 2% pine, with an average number of over 20 thousand plants per hectare. The predominant spruce undergrowth belongs to different size categories. In the 2002 skid trails, forest renewal takes place primarily due to birch and aspen, while the undergrowth represented by pine and spruce is sparce, weakened. The composition of the undergrowth is 36% birch, 26% pine, 22% spruce and 16% aspen, with an average number of 11.5 thousand plants per hectare.

The highest Shannon index is observed in the 1973 skid trails (Table 1), due to the presence of pronounced nano- and microrelief in the sites of this variant (increases from overgrown deadwood and stumps, micro-subsidence and ruts). The state of the 2002 skid trails was very similar, but the diversity index was lower. In this variant, there were more dominant plants in the plots in comparison with the 1973 skid trails.

Table 1.

Characteristics of the grass-shrub layer at the study sites

Location	Number of sub-plots	Species diversity (Shannon index)	Number of species	The ratio of species of different ecological groups		
				forest	meadow	wetlands
Cutting strips	10	1,74	23	99/75*	1/ 1	-
1973 skid trails	9	1,95	26	80/50	12/5	8/5
2002 skid trails	9	1,71	27	74/55	7/1	19/10

*In the numerator - % of the total number of species; in the denominator - projective coverage, %.

The Jacquard index also showed high similarity rates for the cut strips and the skid trails (51.5-53%); however, the 1973 and 2002 skid trails differ significantly (I=39%), which could be attributed to plant succession.

Ecological-cenotic analysis of the grass-shrub layer showed the dominance of the forest group of species in all variants, both in terms of species richness and projective coverage.

A similar ratio of ecological-cenotic groups was also noted within the moss layer (Table 2).

Table 2.

The ratio of ecological-cenotic groups of moss layer at the study sites

Location	Number of species	Ecological and cenotic groups of species			
		forest	wet forests	forest and swamp	forest and meadow
Cutting strips	15	73/55*	13/10	14/15	-
1973 skid trails	18	67/30	14/10	21/35	7/0,1
2002 skid trails	17	70/40	12/10	18/30	-

*In the numerator - % of the total number of species; in the denominator - projective coverage, %.

The forest litter in the skid trails was observed to be thicker than in the cut strips with plant cover restoration (Table 3).

Table 3.

Thickness and bulk density of the forest litter on cutting strips and skid trails of different years of thinning (M±m – mean and standard error, Min-Max – minimum and maximum values, C – coefficient of variation)

Indicator	Cut strips	1973 skid trails		2002 skid trails	
		edge	centre	edge	centre
The bulk density of forest litter, g·cm^{-3}					
M±m	0,115±0,01	0,083±0,007	0,091±0,011	0,151±0,016	0,115±0,012
Min-Max	0,06-0,13	0,037-0,185	0,050-0,228	0,041-0,335	0,065-0,262
C, %	39,1	43,4	47,3	54,3	40,9
Thickness of the forest litter, cm					
M±m	3,73±0,33	10,4±0,79	7,1±0,93	6,3±0,58	6,0±0,57
Min-Max	2 - 6	3-17	1- 22	2-16	2-10
C, %	35,4	42,5	61,5	56,3	44,7

The forest litter thickness increased by 2 times in the 17 years after thinning. Its increase is especially prominent in the ruts of the 46-year-old skid trails. This increase in the thickness of the forest litter is associated with the development of waterlogging and the settlement of *Sphagnum* mosses, as well as detritus from decomposing felling residues. Compaction caused by machinery use in the skid trails is distinguished in the forest litter even 17 years after felling. The values of the bulk density 46 years after thinning are lower than those for the cut strips.

In the skid trails with natural regeneration, the properties of soils at the depths of 0–10 cm and 10–20 cm vary ambiguously. Simultaneously, the compaction caused by machinery use is noted at the depth of 10–20 cm both at 17 years and 46 years after thinning (Table 4). The value of the bulk density is 1.34–1.42 g·cm^{-3}, which is higher than in cutting strips (1.26 g·cm^{-3}).

Table 4.

Properties of soils on cutting strips and skid trails of different years of thinning (M±m – mean and standard error, Min-Max – minimum and maximum values, C – coefficient of variation)

Indicator	Cutting strips	1973 skid trails		2002 skid trails	
		edge	centre	edge	centre
Depth 0–10 cm					
The bulk density, g·cm^{-3}	1,190±0,045	0,848±0,086	0,979±0,101	0,952±0,087	0,872±0,092
Min-Max	0,82-1,38	0,16 - 1,61	0,25-1,65	0,202-1,657	0,189-1,350
C, %	15,0	56,1	41,2	48,5	42,0
Density of the solid phase, g·cm^{-3}	2,458	1,620	2,381	2,306	2,280
Total porosity, %	51,6	47,7	58,9	58,7	61,8
Depth 10–20 cm					
The bulk density, g·cm^{-3}	1,26±0,054	1,408±0,041	1,420±0,072	1,421±0,059	1,335±0,058
Min-Max	0,95-1,59	0,899-1,809	0,817-1,902	1,098-1,754	0,929-1,734
C, %	17,2	15,9	20,21	22,0	17,3
Density of the solid phase, g·cm^{-3}	2,750	2,326	2,516	2,313	2,462
Total porosity, %	54,2	39,5	43,7	38,6	45,8

The most significant changes of the soil occur at the depth of 0–10 cm. The bulk density in the upper layer of the soil is noticeably reduced to 0.85–0.98 g·cm^{-3}, while that of the cut strips is 1.19 g·cm^{-3}.

The results of a one-way ANOVA show that there are differences in the thickness of the forest litter ($H_{(4, N= 128)}$ = 34.33, p = 0.0000) and the bulk density of the forest litter ($H_{(4, N= 104)}$ = 23.05, p = 0.0001), while there are no significant differences in the bulk density at the depth of 0-10 cm ($H_{(4, N= 98)}$ = 5.29 p = 0.2585) and at the depth of 10–20 cm ($H_{(4, N= 98)}$ = 6.61, p = 0.1578). Multiple comparisons of the thickness and the bulk density of the forest litter are shown in Table 5.

The thickness of the forest litter in the cut strips and at the edge of the 1973 skid trails (Z = 5.3, p = 0.0001) differs significantly. The thickness in the centre of the 2002 skid trails and at the edges of the 1973 skid trails also differs (Z =

4.1, p = 0.0005), as does the thickness at the edge of the 2002 skid trails compared with the edge of the 1973 skid trails (Z = 3.8, p = 0.0016).

Table 5.

Results of the Kruskal-Wallis test for multiple comparisons of the thickness and bulk density of the forest litter in different sites (Z – z' values Kruskal-Wallis test; p – probability of rejection of the null hypothesis)

Location	Centre of the 2002 skid trails		Edge of the 2002 skid trails		Centre of the 1973 skid trails		Edge of the 1973 skid trails	
	Z	*p*	Z	*p*	Z	*p*	Z	*p*
Thickness, cm								
Cutting strips	1,50	1,0	2,38	0,1742	2,79	0,0523	5,30	0,0001
Centre of the 2002 skid trails	-	-	0,81	1,0	1,40	1,0	4,10	0,0005
Edge of the 2002 skid trails	-	-	-	-	0,77	1,0	3,78	0,0016
Centre of the 1973 skid trails	-	-	-	-	-	-	2,56	0,1046
The bulk density, $g{\cdot}cm^{-3}$								
Cutting strips	0,49	1,0	0,70	1,0	2,17	0,2970	2,91	0,0367
Centre of the 2002 skid trails	-	-	1,25	1,0	1,68	0,9260	2,35	0,1879
Edge of the 2002 skid trails	-	-	-	-	3,15	0,0165	4,22	0,0002
Centre of the 1973 skid trails	-	-	-	-	-	-	0,45	1,0

There was significant difference in the bulk density of the forest litter in the cut strips and at the edge of the 1973 skid trails (Z = 2.91, p = 0.04). Significant difference was determined between the edge of the 2002 skid trails and the centre of the 1973 skid trails (Z = 3.15, p= 0.02), as well as the edge of the 1973 skid trails (Z = 4.22, p = 0.01).

Discussion

In *myrtillus* type forests, deep ruts are not formed on drained podzolic soils as a result of logging, which has been recognised in the course of this examination immediately after thinning [1]; however, the hardness of the soil in the areas impacted by the driving of skidders was 1.5 times higher. Despite the considerable weight (9.6 tons) of the TDT-55 skidder, the soil pressure of its tracks is no more than 0.45 MPa [14]; this model is considered a relatively light vehicle [22]. According to Cambi et al. [27], logging operations related to tree felling and skidding directly impact the soil cover, irrespective of which technology is used, whether it is the simplest of devices or the most complex and up-to-date machines that use a harvester and forwarder.

The absence of deep ruts was recognised during the excavation of the transverse trenches in the skid trails. In the areas at the edge of the skid trails, disturbances associated with horizons mixing and soil subsidence/compaction were not observed after 17 or 46 years. The average thickness of the mixed horizon in the skid trails is 9–11 cm, with an average coefficient of variability of 36–39%. In the displaced horizons fragments of the forest litter, detritus, podzolic and illuvial horizons in different combinations are observed. Such mixed horizons occur both at the edges of the skid trails (in 77–79% of cases) and in the centre of the skid trails (in 68–72% of cases).

The upper soil horizons mixing, on the one hand, can be favourable for the settlement of trees [10], which was observed under estimation of undergrowth in the skid trails. In the skid trails, the amount of undergrowth is 2–3.5 times more than in the cut strips; this is dependent on the coincidence of the felling and the seed years and increases with the time passed after felling. The renewal of trees in the skid trails begins with birch, which provides the necessary conditions for the settlement of spruce and pine. In 46 years after thinning, spruce prevails in the stand. The species composition of the renewed tree and shrub species corresponds to that of the cutting strips.

On the other hand, soil damage changes the plant cover and can result in changes in the biogeochemical cycles, which has an impact on soil ecosystems [19]. Soil mixing can be accompanied by compaction and result in soil degradation [37] by reducing its porosity and oxygen saturation. This has negative consequences for the productivity of future forests [18; 22].

The upper horizons of the soil and the newly formed forest litter are subject to changes that occur during the restoration of the plant cover and hydrological regime in damaged areas of the skid trails.

Forests of the *myrtillosum* type in the conditions of the northern taiga subzone are characterised by a small number of species in the grass-shrub layer (10–20 species on average) with a pronounced dominance of one or two species. During thinning, new ecological niches appear, which result in an increase in the number of species and a species diversity, that in our case, can be traced by Shannon index values. The highest Shannon index is determined for the grass-shrub layer in the 1973 skid trails; in the 2002 skid trails, the diversity index is lower. Within all of the studied sites, *Vaccinium myrtillus* and *V. vitis-idaea* are dominant, having the highest class of phytocenotic significance. Meanwhile, in the 2002 skid trails, species such as *Equisetum sylvaticum* and *Carex globularis* dominate and have significant phytocenotic significance.

Waterlogging can be observed within cutting areas in the taiga zone [10, 17, 38], which is manifested in the plant cover. In this case, the ecological-cenotic analysis of the grass-shrub layer showed the dominance of the forest group of species in all variants, both in terms of species richness and projective coverage (see Table 1). However, the share of forest species and their coverage decreases due to succession and arrival of species from the group of wetland plants. This group is observed almost exclusively within the watered, overgrown ruts left by the logging machinery and is represented by *Carex globularis* on the skid trails and *C. rostrata*, *C. vulpina, Juncus filiformis* along the edge of the skid trails. A similar ratio of ecological-cenotic groups was also noted within the moss layer (see Table 2). The partial swamping is manifested by the forest-swamp group identified in the skid trails left by the skidder tracks. This group is composed mostly by the species g. *Sphagnum* L. and, to a lesser extent, by g. *Mnium* Hedw. and *Paludella squarrosa* Bridel.

The probability of local gleying and anaerobiosis in flat areas resulting from precipitation accumulation in the ruts and other depressions was indicated by Dymov [5], who conducted studies in similar forest-growing conditions. Even in the absence of deep ruts resulting from skidder use, we recognized development of the waterlogging process in the areas of tractor tracks traveling (the edge of the skid trails) in 46% of cases after 17 years and in 90% of cases after 46 years. Moreover, the thickness of the peat in the 1973 skid trails reaches 20 cm or more, while in the 2002 skid trails, it reaches about 10 cm. In most cases, the formation of new forest litter associated with moisture-loving plants settled in the skid trails after thinning took place.

We found out that, both 17 years and 46 years after the skidder had travelled along the skid trails during the improvement thinning, the bulk density of the 0–10 cm depth layer (topsoil) and of the 10–20 cm depth layer do not differ drastically ($p > 0.05$). However, due to the forest litter mixing with mineral horizons of the soil, organic matter from peat and detritus of felling residues, the bulk density of mineral horizons at the 0–10 cm depth became a little lower (see Table 5). On the 1973 skid trails, waterlogging reduced the density of the solid phase and the total porosity of the mineral soil that is associated with the formation of secondary clay minerals [6]. If the forest ecosystem balance is disturbed as a result of wood harvesting, the organic matter content in the soil may change [31] and its migration within the soil profile may be observed [16, 21]. This is due to the improvement of litter decomposition and humification conditions, increased humidity in the cutting areas and the replenishment of the organic carbon pool in the upper horizons of the soil due to detritus [34].

Despite the absence of statistically significant differences, in the soil layer at a depth of 10–20 cm, the cut strips slight soil compaction and the decrease of total porosity remained at 1.4 g·cm^{-3} and 40%, respectively. Such values of bulk density are critical, as they do not correspond to the optimal values for tree species growth and can produce waterlogging [13].

In the skid trails, especially at their edges where the track skidders were most commonly used, a low and high bulk density in the upper (0–10 cm) and lower (10–20 cm) layers can be seen. In the native soil in the cut strips, the ratio of the soil bulk density in the intervals of 0–10 cm and 10–20 cm is 0.94 g·cm^{-3}, while in damaged soil it reaches up to 0.60-0.68 g·cm^{-3}. Such ratios remain for 50 years. The difference in the soil bulk density contributes to moisture stagnation and the development of waterlogging. Different rates of soil recovery in different soil layers have been identified by Goutal et al. [23].

The recovery of the soil cover in the skid trails to the native state of soils in the cut strips has not been observed for 50 years. It is believed that it may take 30 to 70 years to restore the physical properties [13; 20; 23], and it may take even more time to restore the morphological features of the turbated horizons and the structure of the soil profile [3]. Other authors state that this may take up to 140 years depending on the soil's properties and in some cases, the damage is irreversible [29; 35].

It should be mentioned that the mosaic of the soil cover develops not only over the whole area exposed to felling but also in the skid trails where the machinery moves [28]. The variability of the soil properties in the upper horizons of the skid trails after improvement thinning is much higher than in the cut strips. The coefficient of variability for the bulk density of the soil layer at the 0-10 cm depth reaches 48%, which is three times higher than in the cut strips. This enhances the mosaic conditions and affects the settlement of tree species. At 46 years after cutting, this mosaic is still observed.

Conclusion

The conducted studies have shown that even when using relatively light skidders, as opposed to up-to-date heavy forwarders, for improvement thinning in the northern taiga, significant local changes occur that persist over a 50-year period. On the skid trails, in areas where the soil was impacted by skidder tracks and soil compaction occurred, the ecological and cenotic composition of vegetation changes and the settlement of forest species from the group of wetlands, as well as Sphagnum mosses, are observed. The formation of the forest floor is accompanied by deforestation and local patches of peat soils are formed, which enhances the mosaic of vegetation and soil cover.

After 50 years of successional natural recovery, the impact of logging operations on the soil on the skid trails in a thickness of up to 20 cm is manifested in the presence of mixed horizons and increased bulk of density and in a reduced total porosity, especially in a thickness of 10–20 cm. A disturbance in the balance of the physical parameters in the layers of the root-inhabited soil layer leads to stagnant precipitation, which provokes local waterlogging during the restoration of ruts.

In the Piceeta myrtillosum forest type in the conditions of the northern taiga subzone, the recovery of vegetation and soil cover characteristic of the native forest type has not occurred in 50 years.

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AUTHOR CONTRIBUTIONS

Aleksey S. Ilintsev: field data collection, conceptualization, data interpretation, original draft preparation.

Elena N. Nakvasina: conceptualization, data interpretation, original draft preparation, editing manuscript.

Irina B. Amosova: field data collection, data interpretation, original draft preparation.

ВКЛАД АВТОРОВ

Ильинцев А.С.: сбор полевых данных, общая концепция исследования, интерпретация данных, написание статьи.

Наквасина Е.Н.: общая концепция исследования, интерпретация данных, написание статьи, редактирование статьи.

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