Original scientific paper

Middle-Term Changes in Topsoils Properties on Skidding Trails and Cutting Strips after Long-Gradual Cutting: a Case Study in the Boreal Forest of the North-East of Russia

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Abstract

In this work, physical and chemical properties of the upper horizons of podzolic light loamy soil were investigated 21–23 years after forest cutting. This was after the first shift of long-term, gradual felling was carried out by tree-length logging in wintertime in mixed conifer stands of the Middle Taiga of the Arkhangelsk Region in Russia. The increased density of the forest litter composition was observed. This was especially the case on skidding trails. On the forest floor of skidding trails subjected to a greater stress caused by timber skidding, lower total porosity and aeration porosity was observed, in comparison with the cutting strip and natural forest. It was established that timber skidding during wintertime does not affect the density of podzolic horizon composition. An inverse pattern was observed here: the total porosity and the aeration porosity became higher and were close to the optimum values for plant growth (54.16–52.99% and 15.72–19.97%). In the podzolic horizon on skid roads, comparison to the natural forest showed a significant reduction of phosphorus mobile forms and an increase in the amount of absorbed bases, which is the result of grassy vegetation overgrowth and natural birch regeneration. On skidding trails and cutting strips, the organic matter content and total nitrogen significantly increased, which is related to a change of light intensity, the composition of living ground cover and vigorous decompositions of the organic horizon and woody residues. In cutting areas, a system mosaic of soil cover developed, which differed according to favourable conditions for tree species regeneration, compared to the control stands.

Keywords: boreal forest, forest soil disturbance, skidding trails, cutting strips, long-gradual cuttings

1. Introduction

Different systems of forest cuttings, carried out at a modern technical level, have a significant impact on forest ecosystems (Dymov and Milanovskii 2014, Cambi et al. 2015a, Puettmann et al. 2015). The consequences of soil and forest floor infringements are not only synchronous, but also have a long-term nature, which reveals itself over several decades after logging (Modry and Hubeny 2003, Rozhkov and Karpachevskii 2006), and in some cases have irreversible consequences (Hartmann et al. 2014, Klaes et al. 2016). The main share of the workload falls on forest soils that are susceptible to improper forest management and, in particular, to large-scale harvesting (Cambi et al. 2015a). The bigger the cutting area, the greater are its consequences for the surrounding forest communities. This can cause changes in the microclimate, composition, abundance, and ecology of plants and animals. It is known that the effect of selective cutting is much weaker than that of clear cutting (Pobedinskii 2013).

Logging is mostly carried out by three main systems: Full-Tree (FT), Tree-Length (TL) and Cut-To-Length (CTL) (Karvinen et al. 2006). Each system has its own specific features, which depend on natural and production conditions, technology used and the share of manual operations in the overall process (Gerasimov and Sokolov 2014). In the study region, the proportion of CTL–system is constantly increasing every year, as it has the best efficiency and less impact on the forest environment (Goltsev et al. 2011, Derbin and Derbin 2016). The same trends are observed in Europe and Scandinavia (Leinonen 2004).

In the study area, TL–logging is also a traditional forest harvesting system. This technology is used with chain saws or feller-buncher machines and skidding tractors (skidders). In Russia, 26% of harvested wood is transported to the intermediate warehouses in stems. Meanwhile, in the United States and Canada, the TL –system is continuously improved, its effectiveness increases, and opportunities for further development are visible (Sukhanov 2012). According to various estimates, in the United States, the TL–system ranges from 15 to 85% (Hartsough et al. 1997, Leinonen 2004), in Canada – 85% (Sukhanov 2012).

A wide range of domestic and foreign equipment, wheeled and tracked vehicles, such as harvesters, forwarders, skidders, appears at the logging sites. The degree of impact on soils depends on the type of technology used (Picchio et al. 2012, Marchi et al. 2014, Cambi et al. 2015b). As a rule, stems or logs are delivered to the intermediate warehouses by skidding or forwarding, meaning that vehicles travel on skidding trails. Thus, as a result of heavy machinery movement (harvesters, forwarders, tractors), areas such as skidding trails and wood loading areas are subjected to repeated impact, while the cutting strips are affected to a lesser extent. In recent years, these vehicles are becoming more powerful and economical, but they are also having negative impacts on the soil (Vossbrink and Horn 2004, Horn et al. 2007). The skidding stems stripped forest floor and sometimes organogenic horizon form the compacted and mixed sites. When harvesting, the soil morphology is disturbed in the same as in the case of natural fall-outs of the forests (Karpachevsky 1981). Changing conditions of soil formation during logging activities affect, in varying degrees, the physical, chemical and biological soil properties (Standish et al. 1988, Worrell and Hampson 1997, Powers et al. 2005, Zetterberg et al. 2013, Osman 2013) and composition of the soil cover. Soil properties often largely depend on silvicultural treatments and logging operations, and this may imply soil compaction and consequent restrictions to tree growth and natural regeneration. (Venanzi et al. 2016, Marchi et al. 2016). Soil variations, related to forest harvesting operations, can lead to changes in biogeochemical cycles that affect soil ecosystems (Cambi et al. 2017a). The physical and also morphological properties of the soils are seriously violated on skidding trails and loading sites. A large-scale study in different regions of Russia showed a significant change of water and soil physical properties on clear cutting areas with heavy loam and clay soils (Pobedinskii 2013). Substantial changes of the physical properties of the soils are observed in cuttings areas to a depth of 50–60 cm, and on wood loading sites up to 90 cm (Dymov and Lapteva 2006); changes of the chemical properties are observed up to 30–40 cm (Fedorets and Bahmet 2003). The generally accepted criterion for assessing the impact of logging equipment on soil is the change in its density and associated air, thermal and water regimes of the soil, which affect the soil organisms and plants and have a negative impact on soil properties and forest productivity (Kozlowski 1999, McNabb et al. 2001, Ares et al. 2005, Agherkakli et al. 2010, Cambi et al. 2015a, Cambi et al. 2017b). Many authors (Brais 2001, Akay et al. 2007, Bagheri et al. 2011) noted that compaction, caused by forestry machines, is one of the main causes of soil degradation. The greatest increase in soil compaction occurs at a depth of 10 cm, followed by 20 cm and 30 cm soil layers, respectively (Akay et al. 2007).

After logging, there are significant changes in the nutrients structure in forest floor and upper mineral soil horizons (Fedorets and Bahmet 2003). Clearings of coniferous in boreal forests activated the formation process of podzolic, but after the growth of soft-wooded broadleaved species (birch and aspen) over time an advanced stage of the turf process was observed. The chemical structure of litter also changes due to different species composition of vegetation, dominated by meadow and weeds that appear in forest stands exposed to infringement or in the stand »windows«. These differences determine the character of the litter decomposition, the microflora structure and its activity. Thus, various types of logging can affect forest soils by altering their properties.

It was assumed that:

- ⇒ natural processes of recovery of the upper soil horizon properties will be found two decades after long-term gradual felling carried out in wintertime, but not restored to a natural state of untouched soils
- ⇒ these processes will be different in cutting strips and in skidding trails
- ⇒ the impact on skidding roads will be more considerable than in cutting strips

⇒ the effect on mineral soil horizon will be minimal, both in cutting strips and in skidding roads, as the felling was carried out with a steady snow cover and frozen soil.

2. Material and methods

2.1 Site description and logging method

The research was carried out in the North of the European part of Russia on the territory of the Arkhangelsk Region in forest department of North Arctic Federal University. The object of the study is located in the central part of the Arkhangelsk Region, in Plesetsk administrative district and belongs to the Middle Taiga according to the forest zonation (Kurnaev 1973). The geographical position of the territory is from 62°55′ to 63°10′ North latitude and from 40°15′ to 40°40′ East longitude from Greenwich (Fig. 1).

The climate of the research area is temperate – continental, formed in a small amount of solar radiation in wintertime, under the influence of the Nordic Seas and the intense western removal of moist air masses from the Atlantic ocean (in summer – cold, winter –

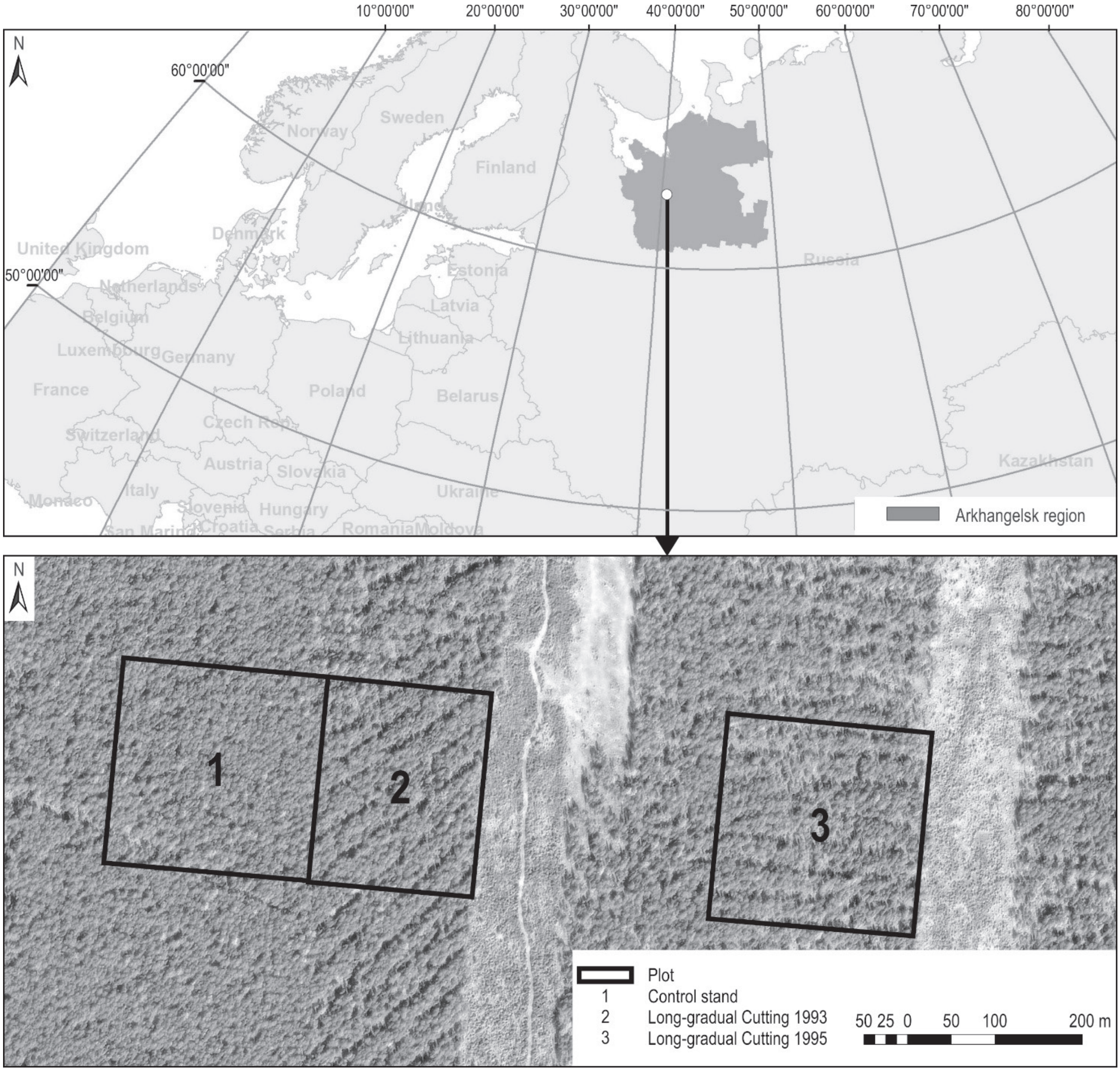

Fig. 1 Location of study area and experimental Long-Gradual Cuttings

warm), and also influenced by local physical-geographical characteristics of the territory. A feature of the climate is a frequent change of air masses of different origin. The average annual air temperature is 0.4°C. The average temperature of the warmest month (July) is +16.1°C, and of the coldest (January) –14.1°C. The annual rainfall is in the range of 380–690 mm, which contributes to the excessive soils moisture, but the natural karst drainage of the study area ensures removal of excess moisture. Winter precipitation occurs mostly in solid form. There is a snow cover from October to April. The average height of the snow cover during winter in the study area is 75–85 cm. The average relative humidity varies during the year from 67% to 87%. Such a high humidity is due to the relative proximity of the seas, numerous rivers, lakes and especially wetlands. The relative proximity of the seas, numerous rivers, lakes and especially swamps contribute to such high humidity. Average annual wind speeds vary from 3–5 m s^{-1} to 7–8 m s^{-1}.

The territory of the study area is characterized by widespread Retisols (94%), less – Gleyic Retisols (5%) and Gleysols (1%), varying in genesis and production values. The upper genetic horizons have fine-textured composition (sandy, loamy, sandy, sandy loams), and the bottom is composed of loams and clay loams.

Coniferous pine (*Pinus sylvestris* L.) and spruce (*Picea abies* /L./ H.Karst) forests, and occasionally larch (*Larix sibirica* Ledeb.) and fir (*Abies sibirica* Ldb.), dominate the study area. Deciduous forests are represented by birch (*Betula pendula* Roth.), aspen (*Populus tremula* L.), alder (*Alnus incana* L.) and willow (*Salix caprea* L.). Deciduous forests are represented by birch, aspen, alder and willow. The share of coniferous tree

Table 1 Brief characteristics of experimental objects (smooth surface, no slope data)

Indicator	Stand untouched by felling	Long-term gradual cutting	
		cutting strip	skidding trail
Forest stands			
Stand composition*, %	57P28S9B6L	55P28S12L5B	–
Average age of stand, years	150	155	–
Average height, m / Average diameter, cm	24/31	24/28	–
Growing stock, m^3 ha^{-1}	539	364	–
Stand density, unit ha^{-1}	968	536	–
Undergrowth			
Undergrowth composition*, %	94S3P3B	62S30B8P sin. L.	79B17S3P1L
Average age of undergrowth, years	25	16	12
Average height, m	1.3	1.5	2.2
Undergrowth density, unit ha^{-1}	1013±102	3747±598	12160±1310
Grass-shrub layer			
Projective cover of herb-dwarf shrub layer, %	75	74	70
Taxa number, unit			
Families	20	14	15
Types	26	18	21
Species	28	22	23
Dominant family (number of species)	*Poaceae* (3), *Orchidaceae* (3), *Pyrolaceae* (2), *Ericaceae* (2), *Scrophulariaceae* (2)	*Asteraceae* (3), *Orchidaceae* (3), *Poaceae* (2), *Ericaceae* (2), *Scrophulariaceae* (2), *Rosaceae* (2)	*Poaceae* (5), *Asteraceae* (3), *Scrophulariaceae* (2), *Ericaceae* (2)
Herbs proportion with turf life form, %	10.7	9.1	21.7

*p – pine, s – spruce, b – birch, L – larch species in the study region is 82.4%, the share of softwood is 17.6%.

The experimental long-term, gradual felling was carried out in 1993 and 1995 in uneven age (from 65 to 202 years) mixed pine-spruce stands growing on Haplic Abruptic Retisols (Loamic) (IUSS Working Group 2015). Logging was done in wintertime, with frozen soil and a steady snow cover. A stand untouched by felling (control) adjoins the western side of the long-term gradual felling and represents original characteristics of harvested stands (Table 1).

The cutting area is designed according to mid-size cutting strips technology; the width of skidding trails does not exceed 5 m, and the width of cutting strips is 30 m. The layout of the trails is perpendicular. The large pine, spruce and birch trees were selected in cutting strips according to the target diameter, and larch trees were cut only on skidding trails. The intensity of the long-term, gradual felling in 1993 was 30% of the growing stock, and long-term, gradual felling in 1995 was 40%. Tree felling was performed with the apex on the trail route at an angle of 60° using chain saws. After that, branches and treetops were cut. Cleaning of felling areas was performed by laying slash residues on skidding trails. Skidding of tree tops was carried out by using cable skidder LTT-55A (mean ground pressure of 50 kPa and 70 kW engine power) with an empty mass of 5800 kg; it moved strictly on skidding trails.

2.2 Soil sampling

Samples of forest floor and soil podzolic horizon were collected in the natural stand, in the cutting strips and skidding trails of stands, after long-gradual cuttings. In 2016, 200 samples of forest floor and soil podzolic horizon were collected – 40 in the control, 80 in cutting strips and 80 in skidding trails. For determining the density of the forest floor, sampling was performed by using frame templates (area of 100 and 144 cm^2). Samples of the podzolic horizon were collected using rigid metallic cylinders (volume of 52.78 cm^3), after removing the forest floor. All samples were weighed on an analytical balance (»moist weight«) (Nakvasina et al. 2007).

2.3 Physical analysis

In the laboratory, the samples were dried at 105°C for 24 h to constant weight (»dry weight«). Physical characteristics were determined by laboratory analyses. Field soil moisture was determined by the following formula:

$$M = \frac{\left(W_\mathrm{W} - W_\mathrm{D}\right)}{W_\mathrm{W}} \tag{1}$$

Where:

M moisture content, %
W_D dry soil (forest floor) weight, g
W_W moist soil (forest floor) weight, g.

The composition density was calculated according to the following formula:

$$D_\mathrm{b} = \frac{W_\mathrm{D}}{V} \tag{2}$$

Where:

D_b bulk density, g cm^{-3}
V volume of cylinder or volume of frame template, g cm^{-3}.

The density of the solid phase (particle density) was obtained by pycnometer method. The composition density and density of the soil solid phase were used to calculate the total porosity, which was determined by the following formula:

$$\varphi = \left(1 - \frac{D_\mathrm{b}}{D_\mathrm{d}}\right) \times 100 \tag{3}$$

Where:

φ total porosity, %
D_d particle density, g cm^{-3}.

Aeration porosity (the share of large pores occupied by air) calculated by the following formula:

$$\varphi_\mathrm{a} = \varphi - M \times D_\mathrm{b} \tag{4}$$

Where:

φ_a is the aeration porosity, %.

2.4 Chemical analysis

To study the chemical characteristics, podzolic horizon was investigated as the first mineral horizon under trees. In this horizon, the main part of sucking roots is located, so changes in the chemical characteristics have a significant impact on further growth and development of plants. Chemical properties were determined for 5 randomly selected samples for each research subject. In total, 25 specimens were studied. The following parameters were evaluated: the amount of phosphorus (P_2O_5) mobile forms and potassium (K_2O), sum of absorbed bases, amount of soil organic matter (C), acidity (pH), hydrological acidity, total nitrogen (N) amount. The methods, generally accepted in Russia and confirmed by state standards, were used. Acidity (pH) was determined by a potassium chloride (KCl) solution in the concentration of 1 mol dm^{-3} at a 1:2.5 ratio of soil to solution, and pH potentiometric was determined using a pH meter with glass electrodes. Hydrolytic acidity was determined (CH_3COONa) in the concentration of 1 mol dm^{-3} at a 1:2.5 ratio of soil to solution with aliquots of extracts titrated with 0.01 M NaOH. Mobile compounds of phosphorus (P_2O_5) and potassium (K_2O) were removed from the soil by the solution of hydrochloric acid (HCl) (extracting solution) in the molar concentration of 0.2 mol dm^{-3}. Phosphorus (P_2O_5) mobile compounds were then determined quantitatively by a photoelectric colorimeter, while potassium (K_2O) was determined by a flame photometer. The amount of absorbed bases is determined in accordance with Kappen method. Soil organic matter was determined by Tyurin method using a photoelectrocolorimeter. Total nitrogen was determined according to the semi-micro-Kjeldahl method.

2.5 Statistical analysis

Statistical analysis of data normality of physical and chemical properties was preceded by Kolmogorov-Smirnov and Sapiro-Wilk tests. The homogeneity of the samples was established by using distributions kurtosis. The data obtained were analyzed by using the STATISTICA® ver. 6.1 (StatSoft Russia). To establish the differences between two mean values, the independent *t*-test at a 0.05 significance level was applied.

3. Results

3.1 Physical properties of forest floor and podzolic horizon

Test results of distribution normality showed that the analyzed distributions do not differ from normal. The Kolmogorov-Smirnov criterion varies from 0.10 to 0.15 (p>0.20), and the Sapiro-Wilk criterion varies from 0.95 to 0.98 (p>0.05–0.80). The kurtosis of curves distribution ranges from –1.00 to 2.20 and does not exceed the empirical limit (–2). This suggests that the statistical sets are homogeneous.

The capacity of the forest floor in the control of the undisturbed stand corresponds to the average data capacity of the forest floor for the middle taiga of Arkhangelsk Region (Table 2). The capacity of podzolic horizon significantly differs from the average horizon size of podzol soils type for midle taiga (Tab. 3). However, this difference is due to the soil genesis and variability within a stands soil cover, which corresponds to distribution limits (3.0 and 12.0), especially on the minimum size of the podzolic horizon often associated with the confinement to large trees. 21–23 years after the first shift of long-gradual felling in wintertime, the capacity of the forest floor on skidding trails is significantly different from the control values ($t_{0.05}$=3.5), and in the cutting strips, the average power corresponds to the natural stands ($t_{0.05}$=0.86). At the same time, increased density is noted on skidding trails compared to the control stand ($t_{0.05}$=–3.48), despite the fact that the logging was carried out during winter and skidding trails were fortified by wood residues. An increased density is also observed in the cutting strips ($t_{0.05}$=–2.14), but *t*-test coefficient is on the border of the confidence interval. The sealing effect of the equipment on the podzolic horizon in the cutting strips and skidding trails was not identified. The change in the total porosity and aeration porosity of

Table 2 Physical characteristics of forest floor and podzolic horizon at the experimental sites (mean ± standard deviation); The average data for mixed pine-spruce forests growing on podzolic soils are given, according to materials for 25 soil profiles (Sklyarov and Sharova, 1970)[1]; Statistically significant differences at the level of 0.05 between the experimental objects after independent *t*-test are marked with an asterisk

Experimental site	Horizon	Thickness, cm	Bulk density, g cm^{-3}	Particle density, g cm^{-3}	Total porosity, %	Aeration porosity, %
Natural stands						
Average data[1]	O	5.24±0.28	–	–	–	–
	El	6.44±0.40	–	–	–	–
Control area	O	4.91±0.21	0.071±0.003	1.433	95.05±0,24	77.80±1.67
	El	4.85±0.31*	1.240±0.030	2.443	49.23±1,22	13.74±1.60
Long-gradual cutting 1993 and 1995						
Cutting strip	O	4.98±0.17	0.080±0.003*	1.366	94.03±0.25*	77.50±1.01
	El	6.05±0.34	1.161±0.021*	2.533	54.16±0.87*	19.97±1.14*
Skidding trails	O	4.17±0.16*	0.118±0.010*	1.544	92.29±0.62*	64.3±1.57*
	El	5.85±0.34	1.176±0.021	2.503	52.99±0.86*	15.72±0.99

Table 3 Results of *t*-test for independent samples (physical characteristics)

Parameters	Experimental site	Horizon	*t*-value	dp	*p*-value
Thickness	Control area	O	0.91	43	0.369413
		El	2.95	43	0.005185*
	Cutting strip	O	0.86	63	0.390818
		El	0.72	63	0.473653
	Skidding trails	O	3.50	63	0.000857*
		El	1.08	63	0.286345
Bulk density	Cutting strip	O	–2.14	58	0.042101*
		El	2.13	58	0.037457*
	Skidding trails	O	–3.48	58	0.000966*
		El	1.70	58	0.095379
Total porosity	Cutting strip	O	2.55	58	0.013411*
		El	–3.28	58	0.001775*
	Skidding trails	O	3.05	58	0.003434*
		El	–2.51	58	0.014771*
Aeration porosity	Cutting strip	O	0.14	48	0.886149
		El	–3.16	58	0.002488*
	Skidding trails	O	4.36	49	0.000066*
		El	–1.10	58	0.275953

**p* values less than 0.05

the upper soil horizons during the formation of cenoses (after cutting) is related to changes of life forms in ground cover and a large amount of birch trees (Table 1). Soft birch litter changes the humification processes in forest litter, compared to natural stands, where litter consists mainly of mosses and conifer litter. The increase in total porosity in the podzolic horizon is rather associated with the appearance of grass having a fibrous root system. The proportion of such grasses is particularly high in skidding trails (21.7%).

On skidding trails, significantly lower values of the total porosity and aeration porosity of the forest floor are observed compared to the background values (Table 3). Packing of forest floor, when cutting and skidding, are not compensated by disintegrating effect of the herbs and soft-leaved breeds litter. In the podzolic horizon, inverse pattern is observed: the total porosity and aeration porosity become higher and are close to the optimum values for plant growth. The technology impact on the horizon overlaps by buffer horizon (forest floor).

3.2 Chemical properties of podzolic horizons

Data analysis for distribution normality showed that the studied distributions do not differ from normal, the Kolmogorov-Smirnov criterion varies from 0.15 to 0.24 (p>0.20), and the Sapiro-Wilk criterion varies from 0.91 to 0.98 (p>0.05–0.8). The kurtosis distribution curves vary from 1.96 to 0.30 and the curves do not break up into two separate curves indicating the population homogeneity.

In the podzolic horizon (Table 4 and Table 5), 21–23 years after long-term gradual felling, the migration of mobile forms of phosphorus ($t_{0.05}$=7.62) is increasing in skidding trails, while maintaining the amount of mobile potassium ($t_{0.05}$=–1.08) and environmental reaction (pH=3.1). However, the increase in the concentration of hydrogen ions is reflected in the hydrolytic acidity increase ($t_{0.05}$=–6.48). At the same time, in the podzolic horizon on skidding trails and cutting strips, there is a significant increase in the quantity of organic matter ($t_{0.05}$=–7.64 and –5.72) and total nitrogen ($t_{0.05}$=–2.97 and –2.59), associated with the illumination

Table 4 Chemical characteristics of podzolic horizon at the experimental sites (mean ± standard deviation); The average data for mixed pine-spruce forests growing on podzolic soils are given, according to materials for 25 soil profiles (Sklyarov and Sharova, 1970)[1]; Statistically significant differences at the level of 0.05 between the experimental objects after independent *t*-test are marked with an asterisk

Experimental site	Contents		Total base absorption	Organic C	pH (KCl)	Hydrolytic acidity	Total N	C/N ratio
	P_2O_5, mg 100 g^{-1}	K_2O, mg 100 g^{-1}	mg-eq per 100 g	%		mg-eq per 100 g	%	
Natural stands								
Average data[1]	–	–	0.76±0.06	1.49±0.07	3.6	6.69±0.09	0.051±0.005	29.21
Control area	15.06±0.21	2.76±0.11	0.54±0.07*	1.61±0.01	3.0	8.80±0.35*	0.057±0.001	28.05
Long-gradual cutting 1993 and 1995								
Cutting strip	15.53±2.19	2.97±0.12	0.91±0.05	2.11±0.04*	3.0	10.60±0.94*	0.072±0.003*	29.31
Skidding trails	9.33±0.51*	2.97±0.12	1.42±0.12*	2.30±0.02*	3.1	10.44±0.13*	0,075±0.001*	30.67

Table 5 Results of *t*-test for independent samples (chemical characteristics)

Parameters	Experimental site	Horizon	*t-value*	dp	*p-value*
P_2O_5	Cutting strip	El	–0.15	13	0.884068
	Skidding trails	El	7.62	13	0.000004*
K_2O	Cutting strip	El	–1.08	13	0.299011
	Skidding trails	El	–1.08	13	0.299011
Total base absorption	Control area	El	2.38	28	0.018268*
	Cutting strip	El	–1.56	33	0.128598
	Skidding trails	El	–5.51	33	0.000004*
Organic C	Control area	El	–0.82	28	0.419425
	Cutting strip	El	–5.72	33	0.000002*
	Skidding trails	El	–7.64	33	0.000000*
Hydrolytic acidity	Control area	El	–2.58	28	0.015371*
	Cutting strip	El	–4.81	33	0.000032*
	Skidding trails	El	–6.48	33	0.000000*
Total N	Control area	El	–0.58	28	0.565015
	Cutting strip	El	–2.59	33	0.014319*
	Skidding trails	El	–2.97	33	0.005494*

**p* values less than 0.05

change, composition of ground cover and vigorous decomposition of the organic horizon and woody residues. The C/N ratio in the soil on skidding trails is increased, reaching 30.69 vs. 28.05–29.21 in natural stands, which generally means reducing the enrichment of humic substances with nitrogen in this microsite. Changing of soil formation conditions related to the illumination and changes in vegetation leads to an increase in the amount of absorbed bases and soil saturation level in the podzolic horizon, which is especially evident on skidding trails. After 21–23 years, the sum of exchange bases is 3 times higher in podzolic horizon on skidding trails than the background values in natural stands, and the level of saturation with bases – 2 times higher, reaching values not typical for the natural soil (1.42 mmol per 100 g of soil and 12%, respectively).

4. Discussion

The analyzed physical properties (composition density, solid phase density, total porosity, aeration porosity) are the most illustrative for assessing the impact of logging equipment on forest soils (Cambi et al. 2015a). For example, the main reason for poor plant growth is the nutrients unavailability, as by increasing the composition density, pores and humidity are reduces, which affect the plants root system (Šušnjar et al. 2006). Recent studies (Cambi et al. 2017b) showed that limited access and acquisition of nutrients and water due to the shorter length of main root likely played a key role for the growth and physiological responses to soil compaction in *Q. robur* seedlings. Reduction of soil compaction and total porosity are the inevitable consequences in skidding places, and can vary in intensity and distribution as the result of interaction between machine and local factors during timber harvesting. The impact level depends on many factors, such as the number of skidder passes, skidding track tilt, places, characteristics, logging equipment, skid trails location and harvesting season (Laffan et al. 2001, Demir et al. 2007, Najafi et al. 2009, Solgi and Najafi 2014). Thus, soil compaction can lead to mass reduction of roots in the upper soil horizons (Karpechko 2008), which is visible as density is increased by 15% or more (Page-Dumroese et al. 1998). However, when logging in wintertime, when the soil is frozen and covered with snow, the impact of logging machines on soil and roots is considerably lower.

We found saving seals of the forest floor two decades after cutting, which affects the reduction of total porosity in cutting strips and skidding trails, which is in agreement with the opinion of several authors (Ares et al. 2005, Ampoorter et al. 2007, Picchio et al. 2012). It may be due to the change in the number of macropores (Seixas and McDonald 1997, Ampoorter et al. 2007).

The impact of logging equipment that lasted for 21–23 years, after the cuttings, is not included into the density composition of podzolic horizon, because there was no direct exposure to skidding equipment on the roads in wintertime. However, the density of podzolic horizon composition at the studied sites is less than 1.4 g cm^{-3}, which indicates the disposition of the horizon to compaction (Powers et al. 2005).

Similar results were obtained when logging in cold weather (–20°C) with stable snow cover in the beech forests of the Czech Republic (Modry and Hubeny 2003). Frozen ground and snow cover provide the best carrying capacity (Ballard 2000). Trail works in wintertime on frozen soil are more effective and cause less damage to the soil surface (Šušnjar et al. 2006).

The aeration porosity of podzolic horizon in all studied sites is low (13.74–19.97%). It is a dynamic component of the soil and changes depending on external factors. In our experience, first of all, a low proportion of pores saturated with air is related to rain, which passed before samples were collecting. The average aeration porosity for loamy mineral soil is 25% (Osman 2013). When the aeration porosity is reduced to 15%, the reduction in root growth is noted (Richards and Cockroft 1974). The trees roots typically operate at oxygen levels over 10% (Kozlowski 1985).

Logging can lead to the disturbance of upper soil horizons, with subsequent increase in mineralization and certain nutrients leaching (phosphorus, potassium, etc.), which usually lasts for 2–5 years. Later, there may be changes in the soils nutrient regime, as this process is reversible (Worrell and Hampson 1997) and related to changes in site vegetation.

20 years after logging on skidding trails, a significant reduction of phosphorus mobile forms has been observed in podzolic horizon, amounting to 9.33 mg 100 g^{-1} compared to 15.53 mg 100 g^{-1} in the control. At the same time, the amount of mobile potassium remains quite stable at 2.97 mg 100 g^{-1} (2.76 mg 100 g^{-1} in the control). Other authors (Naghdi et al. 2016) similarly show that, on skidding trails, after the summer works depending on the number of skidder passes and slope, the reduction of phosphorus ranges from 11.5–44.5% and of potassium from 8.7–51.4% of the undisturbed area. The mobility of phosphorus is caused by acidic environment (pH=3.0) (Lambers et al. 2011). Based on the acidity degree, the studied sites are highly acidic (pH=3.0–3.1). Most forest soils have a pH of 3 to 7 (Osman 2013). Our research has shown that the environmental reaction in stands continues after long-term gradual felling. Similar results have been obtained for winter logging (Modry and Hubeny 2003).

The increase in the amount of soil organic matter is observed in the podzolic horizon both in cutting strips and skidding trails (2.11–2.30%), compared to the control stand (1.61%). This is related to changes in the species composition of lower storeys vegetation, increasing in grass and leafy litter, soil moisture and forest floor decomposition. As noted (Aragon et al. 2000, Arthur et al. 2013), soil organic matter acts as a link in forest soils, at least in the upper layer of the soil. Change and movement of organic matter in the soil profile occur in cutting areas (Dymov and Lapteva 2006, Dymov and Milanovskii 2014), which may have negative consequences for soil structure and result in susceptibility to compaction (Cambi et al. 2015a). Mobility of humic substances contributes to the eluviations process. However, some studies show that, 17 years after wood harvesting, depletion of C and N were observed in cutting place compared to the control area (McLaughlin and Phillips 2006). The amount of organic matter in forest soils is usually 1–5% of the dry weight and it decreases with depth. Under natural conditions, the organic matter in the soil is stable, but when the balance of forest ecosystems is infringed, this indicator can change (Osman 2013).

It is known that organic matter is closely related to gross nitrogen in soils. In cutting strips and on skidding trails, 21–23 years after long-gradual felling, a larger amount of total nitrogen has been observed in the podzolic horizon (0.072–0.075%), compared to the control (0.057%). The source of total nitrogen in the soil is mainly the forest floor material (Fedorets and Bahmet 2003). The main reason is the increase of mosses and herbaceous protective cover. So, on skidding trails, there are some kinds of herbs that are not marked in natural plantings (*Trifolium repens*, *Ranunculus acris*, *Lathyrus pratensis*, *Deschampsia cespitosa*, *Calamagrostis epigeios*, *Chamaenerion angustifolium*), and there is an increase in birch litter, which contained more nitrogen than the needles (Marschner 2012, Osman 2013). Approximately one-third of the total nitrogen consumed by plants over the growing period is returned with litter (Fedorets and Bahmet 2003).

C:N relationship indicates the nitrogen amount in the humus. The optimal value is 10 (Fedorets and Bahmet 2003). Changes of soil properties and vegetation composition have led to C:N ratio conversion. Its increase is observed in the skidding trails (30.67) compared to natural stands (29.21), which suggests that mineralization is slower, and therefore a small amount of mineral nitrogen is produced. An inverse relationship was established (Bolat et al. 2015) on the skid road and tractor road in oak forests of Turkey, where there was a lower C:N after a summer harvesting performed to reduce the vegetation cover.

Skidding trails, with clear cutting of trees, and wood residuals stowage have undergone significant changes in the formation of new stand, compared to the cutting strips. Therefore, the processes of vegetation formation and evolution of soil formation differ markedly. As a result, a system of sites with different vegetation and soil properties is formed on the cutting area. Irregular stands are created (system diversity of vegetation and forest floor), which persist for a long period (at least 20 years after logging).

5. Conclusions

Our research shows that long-term gradual cutting by tree-length system in wintertime in mixed conifer stands on podzolic soils in the middle taiga, on skidding trails and cutting strips, results in changes in physical and chemical properties of upper soil horizons, which persist for more than two decades. Significant differences compared to native stand and cutting strip have been observed in skidding trails, subjected to the repeated passage of heavy equipment transporting trees. The site with trees completely cut down is overgrown usually by birch and by grasses that change the processes of soil formation.

The forest floor in the cutting strips and skidding trails maintains the increased density, and the reduced total and aeration porosity. Podzol horizon lying under the forest floor is much less affected. The effect on the podzolic horizon is contrary to the effect on the forest floor: total and aeration porosity becomes higher and close to the optimum values for the growth of plants. The concentration of hydrogen ions increases, which is reflected in the raising of hydrolytic acidity, the amount of organic matter and total nitrogen. In the podzolic horizon on the cutting strips, migration of phosphorus mobile forms is enhanced, while the mobile potassium and environmental reaction maintain the same values. The amount of absorbed bases and soil saturation level are increased to values not characteristic for natural coniferous stands of the middle taiga.

The vegetation diversity and soil cover, formed as a result of logging, create a system mosaic of sites that should be considered when monitoring and implementing economic activities in the stands, after long-gradual cuttings. Further research on the change and recovery dynamics of physical and chemical characteristics of forest soils over time after logging is needed to obtain a more complete understanding of the soil and vegetation self-regeneration processes in cutting areas.

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