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SOIL CHEMISTRY

Dynamics of Water-Soluble Carbon and Nitrogen Content in Soils in the First Years after Clearcutting

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Abstract—Logging is one of the main anthropogenic factors that change forest ecosystems. An experiment was launched to study the effect of logging equipment on soil properties after cutting spruce forests in the middle taiga of the Komi Republic, during which skidding trails with different number of wheeled vehicle passes (forwarder PONSSE ELEPHANT) were set. Carbon (C_{ws}) and nitrogen (N_{ws}) of water-soluble compounds play an important role in the global cycle of elements. The paper presents the results of observations over the water-soluble organic matter content in the soils of original forests (podzolic soils—Albic Retisols) and the soils at different technological sites of the logging area that have experienced different loads, i.e., cutting strips and skidding trails with three passes of logging equipment (podzolic soil), ten passes (turbozem), and passes followed by leveling (turbozem). A significant increase in total carbon was revealed in soils in the first two years after cutting. The greatest changes were registered in the upper mineral horizons (EL and TUR_{cwd}), in which the carbon content increased 3–6 times (0.32–2.2%) versus 0.45% in the original forest soil. A considerable rise in the C_{ws} content was found in organic and mineral soil horizons (up to 33.4 and 0.46 mg/g, respectively) after clear cutting, which thrice on average exceeds the initial values. The content of water-soluble nitrogen increases from 0.23 to 2.12 mg/g in the organic horizon two years after tree cutting. In the mineral horizons, the N_{ws} content varied from 0.003 to 0.020 mg/g after cutting (versus 0.002–0.011 mg/g in the original forest soil). It is shown that an increase in water-soluble carbon and nitrogen contents can be considered a significant criterion of changing soil organic matter due to logging activities, since their concentrations differ substantially from the initial values.

Keywords: clear cutting, field experiment, cutting strips, technological zones in logging area, forms of carbon and nitrogen, podzolic soils, water-soluble organic matter, Albic Retisols

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INTRODUCTION

Taiga ecosystems are subject to various types of anthropogenic activities, being at the same time the sensitive indicators of modern climate change [49]. Logging activities are one of the main anthropogenic factors changing forest ecosystems. Clear cutting transforms significantly the forest cover and forest soils [4, 7, 12]. The area of cutting strips is known to constitute up to 59–71%, and that of skidding trails, 18–29% of the total logging area [4, 14]. The soils at cutting plots do not experience a direct impact of heavy logging machinery, unlike the soils within skidding trails, which are disturbed most of all. The number of wheeled equipment passes becomes an important parameter [8, 9, 65, 67], which causes mixing up the litter with the mineral soil horizons, as well as penetration of logging residues deep into the soil profile upon multiple passes of heavy logging equipment [15].

Due to significant carbon reserves concentrated in forest ecosystems, a lot of studies have been devoted to the content of soil carbon compounds and changes in their composition [4, 16, 24, 42, 57, 59]. The soils of forest ecosystems in the boreal zone contain approximately 30% of the planetary carbon reserves [64]. However, not so many studies deal with assessing the logging impact on the composition and properties of soil organic matter in the European north [6, 8]. Carbon of water-soluble compounds appears to be one of the most active and mobile sources of this element; it is a labile form quickly transformed in soils [18, 19, 47, 56], and it plays an important role in the global carbon cycle [23, 32, 46, 48].

Mineralization of water-soluble organic matter (WSOM) affects significantly the carbon loss from terrestrial ecosystems, including forests [29, 32]. SOM preservation and accumulation can influence the

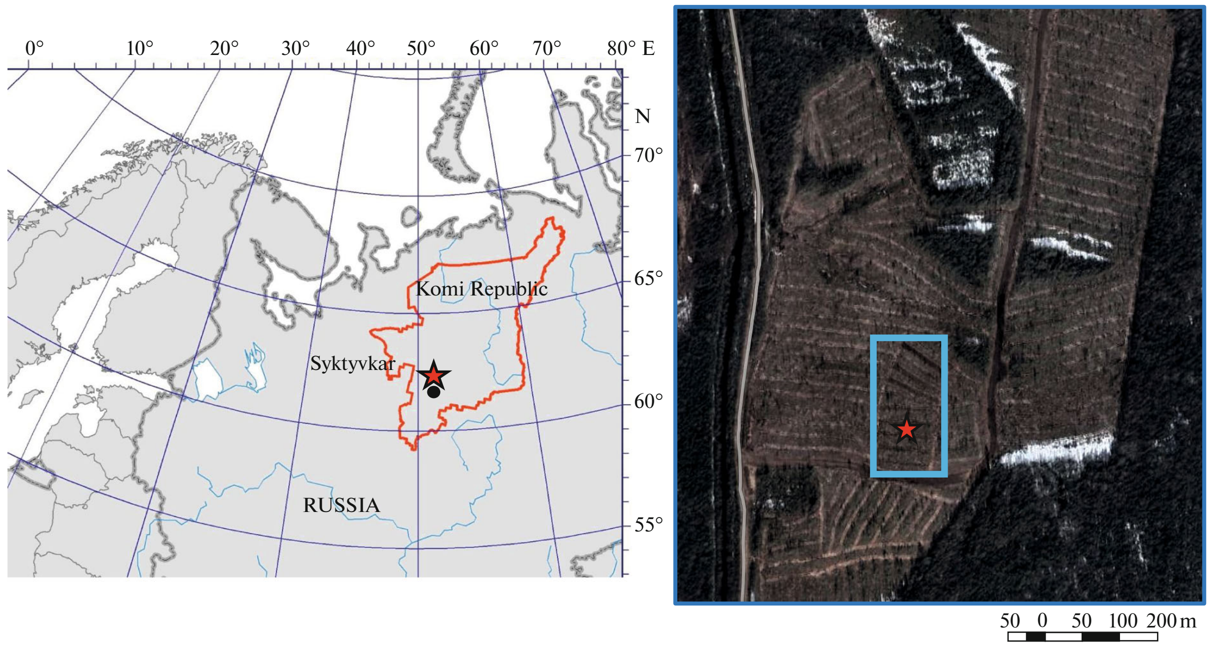

Fig. 1. Location of the cutting area and the study object. The site image is taken from Google maps.

functions and nutritional regime of soils [43]. Thus, SOM participates in forming the chemical composition of soils and transports substances in the soil profile [20, 29, 54]. SOM is the most important substratum for microorganisms [10, 21, 22, 25, 28, 37]. Currently, this parameter is often used as an indicator of microbial activity [3, 30]. The studies by both Russian and foreign researchers have pointed out the important functions of WSOM as the most dynamic fraction of soil organic matter, which indicates changes in WSOM and soil formation as a whole [10, 13]. It has been shown that its transformation can be considered as a marker for monitoring adverse effects on soils [66, 45]; whereas experimental and model research in WSOM dynamics permits assessing its concentrations and input to the global carbon cycle [40].

Proceeding from the analysis of publications, it is assumed that the data on the WSOM content and its change upon widespread logging activities in the European northeast of Russia are relevant for obtaining new information and distinguishing WSOM as an indicator of anthropogenic impact (logging, wildfires, and agricultural use). Research in assessing the seasonal dynamics of WSOM remains acute, as it may contribute to deeper understanding of these processes and their impact on the functioning of soils.

This work is aimed at assessing the change in the carbon and nitrogen contents in water-soluble compounds of soils after cutting blueberry–green moss spruce forests in the middle taiga of the Komi Republic.

OBJECTS AND METHODS

The research was carried out in the middle taiga subzone of the Komi Republic in 2020–2022. The climate of the study area is moderately continental and moderately cold. The mean annual air temperature is +0.4°C, the mean e monthly temperature is +16.7°C in July and –15.2°C in January. The annual precipitation amounts to 560 mm, evaporation constitutes 442 mm, and the moisture coefficient is equal to 1.27, which attests to excessive moisture [1, 2]. According to the soil-geographical zoning, the study area is located in the southern part of the Vym-Vychegda okrug of typical podzolic soils, iron-illuvial podzols, and peaty-podzolic gleyic illuvial-humus soils. The objects of the study were located on the top of a moraine ridge. The territory belongs to the Vychegda–Mezen Plain, with fluvioglacial loamy-clayey homogeneous and layered sediments as soil-forming rocks [1] (Fig. 1).

Initially (2020), a podzolic soil developed in a blueberry–green moss spruce forest was described in the study area. In winter 2020/2021, tree felling was performed in the study area with the use of multi-operational equipment (forwarder and harvester machines). The study was carried out in different technological logging areas (Fig. 2): the cutting area (C) and the trailing area with different number of passes of wheeled vehicles. The skidding trails varied in the mechanical disturbance degree: three (3P) and ten (10P) passes of heavy logging equipment; trails with ten passes followed by surface leveling (reclamation) (10R) were also studied. A four-axle Ponsse Elephant Erg08w A090626 (22.8 t) forwarder was used as an experimental machine for modeling trails. Before passing, the

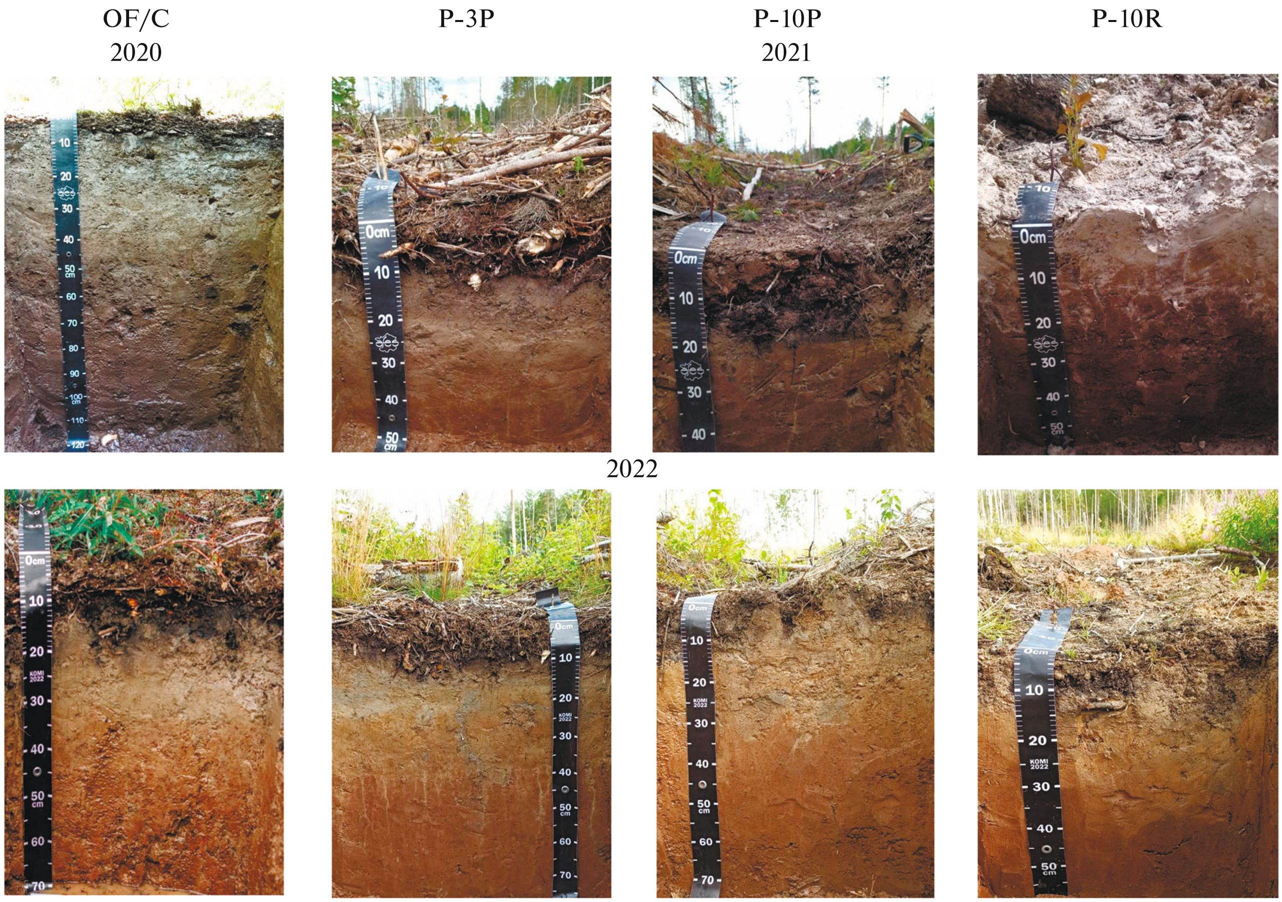

Fig. 2. Profiles of the studied soils. OF, original forest; C, cutting strips; 3P, soil profile in the skidding trail with three passes; 10P, soil profile in the skidding trail with ten passes; 10R, soil profile in the skidding trail after ten passes and subsequent leveling.

forwarder was loaded with aspen pulpwood. A total weight of the forwarder with timber was 36.3 tons. A reference soil pit was dug within each technological zone of the logging area for full-profile sampling once per field season. For the original forest site and the subsequent cutting strips, soil pits were made in 2020, 2021 and 2022. Within skidding trails, full-profile soil pits were laid in 2021 and 2022. The soil profiles were set in ruts, as the inter-rut space remained undisturbed mechanically. To study the dynamics of water-soluble carbon and nitrogen, samples were taken from the litter and the upper mineral soil horizons of the cutting strips (the eluvial EL horizon) and skidding trails (the turbated horizon TURcwd) every month from May to October, i.e., six samples annually (in 2021, from June to September—five samples) for two years after clear cutting. To take into account the seasonal dynamics of C_{ws} and N_{ws}, the sampling location was determined randomly within the technological units of the logging area.

More detailed evidence about the study site and the experiment on the effect of the number of passes on soil properties was provided in [8].

Chemical analysis of soils was carried out in the certified eco-analytical laboratory and the Soil Science Department at the Institute of Biology, Komi Research Center, Ural Branch, Russian Academy of Sciences. The total content of carbon (C_{tot}) and nitrogen (N_{tot}) in the samples of reference pits was found using an EA-1100 (Carlo Erba) analyzer. To determine the content of total carbon and nitrogen, a mixed sample was taken from each genetic horizon of the profile. The content of water-soluble carbon (C_{ws}) and nitrogen (N_{ws}) with the account of seasonal dynamics (n = 5–6), was measured with a TOC-VCPN analyzer (Japan, Shimadzu) equipped with a TNM-1 module. Results are presented for a significance level $P = 0.95$. Water-soluble substances were extracted by deionized water (ELGA Lab Water, England) in BIOFIL tubes at room temperature upon a soil-to-water ratio of 1 : 50 and 1 : 100 for mineral and organic horizons, respectively. The suspensions were shaken for an hour on a Heidolph Multi Reax shaker (6X speed, 4600 rpm) at room temperature. Filtration was carried out immediately after shaking on Millipore units using quartz filters (MN, Germany, with a pore size of 0.4 μm). The data were recalculated for air-dry samples.

Table 1. Contents of total carbon (C_{tot}) and nitrogen (N_{tot}) in the soils of original forests and cutting strips

Profile	Year	Horizon	Depth, cm	C_{tot}	N_{tot}	C/N
				%		
OF	2020	O(L)	0–1	42.90 ± 1.50	1.73 ± 0.19	29
		O(F)	1–4	44.50 ± 1.60	1.72 ± 0.19	30
		O(H)	4–5	34.40 ± 1.20	1.10 ± 0.12	36
		EL1	5–20	0.45 ± 0.10	0.04 ± 0.01	14
		EL2	20–45	0.16 ± 0.04	0.02 ± 0.01	9
		BEL	45–65	0.21 ± 0.05	0.02 ± 0.01	11
Cutting strips	2021	O(L)	0–1	44.80 ± 1.60	1.90 ± 0.21	28
		O(F)	1–4	44.40 ± 1.60	1.60 ± 0.18	32
		O(H)	4–5	40.00 ± 1.40	1.22 ± 0.13	38
		EL1	5–20	0.31 ± 0.07	0.02 ± 0.01	14
		EL2	20–45	0.54 ± 0.12	0.03 ± 0.01	19
		BEL	45–65	0.11 ± 0.03	0.02 ± 0.01	7
	2022	O(L)	0–1	14.90 ± 1.50	0.60 ± 0.12	29
		O(F)	1–4	33.40 ± 1.20	1.14 ± 0.13	34
		O(H)	4–5	39.40 ± 1.40	1.11 ± 0.12	41
		EL1	5–20	0.93 ± 0.21	0.05 ± 0.01	23
		EL2	20–45	0.46 ± 0.11	0.04 ± 0.01	14
		BEL	45–65	0.12 ± 0.03	0.02 ± 0.01	9

OF means original forest, ±Δ are the limits of the absolute error interval at $P = 0.95$. Dash designates no data available.

Block graphs were built in the Statistica 10.0 program to compare differences between the study sites and median values and to find scattering of values. Distribution diagrams were constructed in Microsoft Excel 2010.

RESULTS AND DISCUSSION

Physicochemical properties of soils. The effect of tree cutting on the physicochemical properties of soils was described earlier [8]. Some physicochemical parameters are listed in Table 1. It is shown that the soil in cutting strips was moderately acid (4.2–5.5 pH_{H_2O}) in the first year after cutting. Two years after cutting, in 2022, pH_{H_2O} varied from 4.4 to 5.7 by the soil profile at the cutting site. Two years after cutting, the chemical properties of soils within skidding trails showed a number of differences both from the background values and those one year after cutting. In the skidding trail soil with three passes, pH_{H_2O} varied within 4.4–5.8 and 4.7–5.4 in 2021 and 2022, respectively. The 10P soil showed certain acidification of the upper turbated horizon to pH 4.7 in 2021 and pH 4.8 two years after cutting as compared to R-10R soil, because the organic horizon was mixed up with the upper mineral horizon rather than destroyed completely. In 10R soil, pH_{H_2O} varied within 5.0–5.2, which is typical for middle-profile mineral horizons.

Analysis of particle-size distribution revealed some increase in the content of physical clay (<0.01 mm) in the mineral horizons of skidding trail soils as compared to the original soil before logging. The distribution of physical clay fraction is uniformly eluvial with an increase in the lower mineral horizons. In addition, a 1.2–5.0 time rise in the content of clay t fraction (<0.001 mm) was noted for the middle and lower mineral horizons of soils in the dragging area. The clay fraction content varied from 13 to 44% in 3P soils, and from 19 to 46%, in 10P soils. The 10P site showed the maximum increase in the clay fraction content as to the background soil, i.e., 27–60%. Wheeled vehicles by pressing and mixing are likely to promote the migration of clay particles down the soil profile. Thus, the soils of dragging areas show a heavier texture (sandy loam to light clay) as compared with the original soil (sandy loam to silty loam).

Contents of total carbon and nitrogen. The original podzolic soil is characterized by a regressive-accumulative distribution of carbon and nitrogen in the profile with maximum concentrations in the litter and a decrease in the mineral horizons. This is typical for this soil type formed in bilberry–green moss spruce forests and agrees with published data [58, 33].

The carbon content in the original soil before forest cutting (OF) varied from 34.4 to 45.4% in the litter, and from 0.16 to 0.45% in mineral horizons (Table 2).

Table 2. Contents of total carbon (C_{tot}) and nitrogen (N_{tot}) in the soils of skidding trail areas

Profile	Year	Horizon	Depth, cm	C_{tot}	N_{tot}	C/N
				%		
3P	2021	O(L)	0–2	47.00 ± 1.60	1.24 ± 0.14	44
		O(F + H)	2–5	42.50 ± 1.50	1.25 ± 0.14	40
		EL1	5–15	0.65 ± 0.15	0.05 ± 0.01	15
		EL2	15–25	0.15 ± 0.03	0.02 ± 0.01	10
		BEL	25–35	0.14 ± 0.03	0.02 ± 0.01	9
		BT	35–50	0.16 ± 0.04	0.02 ± 0.01	8
	2022	O(L)	0–2	35.90 ± 1.30	1.23 ± 0.14	34
		O(F + H)	2–5	39.30 ± 1.40	1.33 ± 0.15	34
		EL1	5–15	0.83 ± 0.19	0.04 ± 0.01	25
		EL2	15–25	0.38 ± 0.09	0.03 ± 0.01	15
		BEL	25–35	0.17 ± 0.04	0.02 ± 0.01	9
		BT	35–50	0.26 ± 0.06	0.03 ± 0.01	9
10P	2021	TURcwd	0–15	2.20 ± 0.30	0.11 ± 0.02	23
		EL	15–20	0.27 ± 0.06	0.03 ± 0.01	12
		BEL	20–30	0.18 ± 0.04	0.03 ± 0.01	8
		BT	30–50	0.15 ± 0.03	0.03 ± 0.01	7
	2022	TURcwd	0–15	6.30 ± 0.60	0.24 ± 0.05	31
		EL	15–20	0.53 ± 0.12	0.04 ± 0.01	15
		BEL	20–30	0.27 ± 0.06	0.03 ± 0.01	11
		BT	30–50	0.17 ± 0.04	0.03 ± 0.01	7
10R	2021	TURcwd	0–10	0.32 ± 0.07	0.03 ± 0.01	12
		BEL	10–20	0.25 ± 0.06	0.04 ± 0.01	8
		BT	20–50	0.17 ± 0.04	0.04 ± 0.01	6
	2022	TURcwd	0–10	2.00 ± 0.30	0.11 ± 0.02	21
		BEL	10–20	0.48 ± 0.11	0.05 ± 0.01	12
		BT	20–50	0.36 ± 0.08	0.05 ± 0.01	9

3P designates the profile in the skidding trail zone with three passes; 10P designates the profile in the skidding trail zone with ten passes; 10R designates the profile in the skidding trail zone with ten passes and the subsequent leveling (reclamation). ±Δ are the boundaries of the absolute error interval at $P = 0.95$. Dash designates no data available.

The nitrogen content ranged within 1.10–1.73 and 0.021–0.037%, respectively. The carbon content in the litter and mineral horizons of the cutting strip soil one year after tree cutting was close to that in the original forest soil. In the first year after cutting, the carbon content in the organic soil horizon of cutting strip ranged from 40.0 to 44.8%. The nitrogen content varied within 1.22–1.90%. Somewhat higher carbon content in the upper litter subhorizon is probably due to the input of logging residues, pine needles, and leaves [6]. The content of C_{tot} and N_{tot} decreases in the mineral horizons (0.110–0.54% for carbon and 0.019–0.033% for nitrogen). Two years after cutting, the carbon content varied from 14.9 to 39.4% in the litter. In the mineral horizons, the content of C_{tot} ranged from 0.12 to 0.93% and N_{tot}, from 0.016 to 0.048%. Decreasing C_{tot} in the upper litter subhorizon in the second year after cutting is probably due to the growing light-loving herbaceous species *Avenella flexuosa* (meadow grass) in the ground cover. The work [17] shows that litters with a high content of herb residues differ from typical forest litters in the lower carbon concentrations. This testifies to different proportions of initial organic substances in litters, i.e., a higher share of lignin in forest litters and cellulose in herb litters [17]. The carbon content was found to have almost doubled in the upper mineral EL horizon two years after logging (up to 0.93 ± 0.21%) as compared to the initial values (up to 0.45 ± 0.10%). This is probably due to the greater saturation of the horizons with organic matter upon decomposition of logging residues in the second year after cutting. No significant changes were detected in the nitrogen content.

Table 3. Some physicochemical properties of the studied soils

Profile	Year	Horizon	Depth, cm	pH_{H_2O}	Content of particles, %	
					<0.01	<0.001
OF	2020	O(L)	0–1	5.3 ± 0.1	–	–
		O(F)	1–4	4.5 ± 0.1	–	–
		O(H)	4–5	4.3 ± 0.1	–	–
		EL1	5–20	5.0 ± 0.1	19	9
		EL2	20–45	5.7 ± 0.1	28	9
		BEL	45–65	5.8 ± 0.1	20	8
Cutting strips	2021	O(L)	0–1	5.4 ± 0.1	–	–
		O(F)	1–4	4.6 ± 0.1	–	–
		O(H)	4–5	4.2 ± 0.1	–	–
		EL1	5–20	4.6 ± 0.1	8	3
		EL2	20–45	5.0 ± 0.1	8	4
		BEL	45–65	5.5 ± 0.1	35	12
3P		O(L)	0–2	5.1 ± 0.1	–	–
		O(F + H)	2–5	4.4 ± 0.1	–	–
		EL1	5–15	4.7 ± 0.1	13	5
		EL2	15–25	5.4 ± 0.1	25	5
		BEL	25–35	5.7 ± 0.1	33	15
		BT	35–50	5.8 ± 0.1	44	27
10P		TURcwd	0–15	4.7 ± 0.1	22	9
		EL	15–20	5.3 ± 0.1	19	7
		BEL	20–30	5.7 ± 0.1	44	23
		BT	30–50	5.9 ± 0.1	46	28
10R		TURcwd	0–10	5.1 ± 0.1	27	5
		BEL	10–20	5.5 ± 0.1	60	41
		BT	20–50	5.7 ± 0.1	58	40

OF means original forest, ±Δ are the limits of the absolute error interval at $P = 0.95$. Dash designates no data available.

The contents of carbon and nitrogen in the soils of skidding trail plots (Table 3) also change: their increase in the upper mineral horizons is observed. The carbon and nitrogen content is maximally close to the initial values in the soil with three passes (3P). This may be due to the lower anthropogenic load on this plot. A year after cutting, the litter of 3P soil showed 42.5–47.0% carbon and 1.24–1.25% nitrogen. In the mineral horizons, the carbon content varied from 0.14 to 0.65% and the nitrogen content, from 0.017 to 0.049%, which corresponds to the values in the original forest soil. Two years after cutting, the element distribution patterns by the soil profile were close to the initial ones, with a somewhat lower carbon content in the litter (35.9–39.3%) and higher carbon content in the upper mineral horizons (0.17–0.83%).

The main changes were observed in soils within skidding trail plots with ten passes of wheeled logging machinery. A year after cutting, the carbon content in the turbated TUR_{cwd} horizons of 10P and 10R soils ranged from 0.32 to 2.2% ; the nitrogen content, from 0.031 to 0.112%, which was due to mixing of litters with the upper mineral horizons. In the 10P soil, the C_{tot} content rose to 6.3 ± 0.6% in the TUR_{cwd} horizon. In the lower mineral horizons, the values remained virtually unchanged. In the soil at the reclaimed site, the carbon content was equal to 2.0 ± 0.3% in the upper mineral horizon. The carbon content also increased in the lower mineral horizons (0.36–0.48%). Similar patterns were revealed for the nitrogen content in the soils of skidding trail zone with ten passes of wheeled vehicles.

The change in the carbon and nitrogen contents may be represented most vividly by analyzing their median values in the upper mineral horizon EL (TUR_{cwd}) (Figs. 3a and 3c), which have been maximally transformed by the mechanical impact of wheeled vehicles (turbation, mixing). Median values of the total carbon content C_{tot} in the upper mineral horizons can be

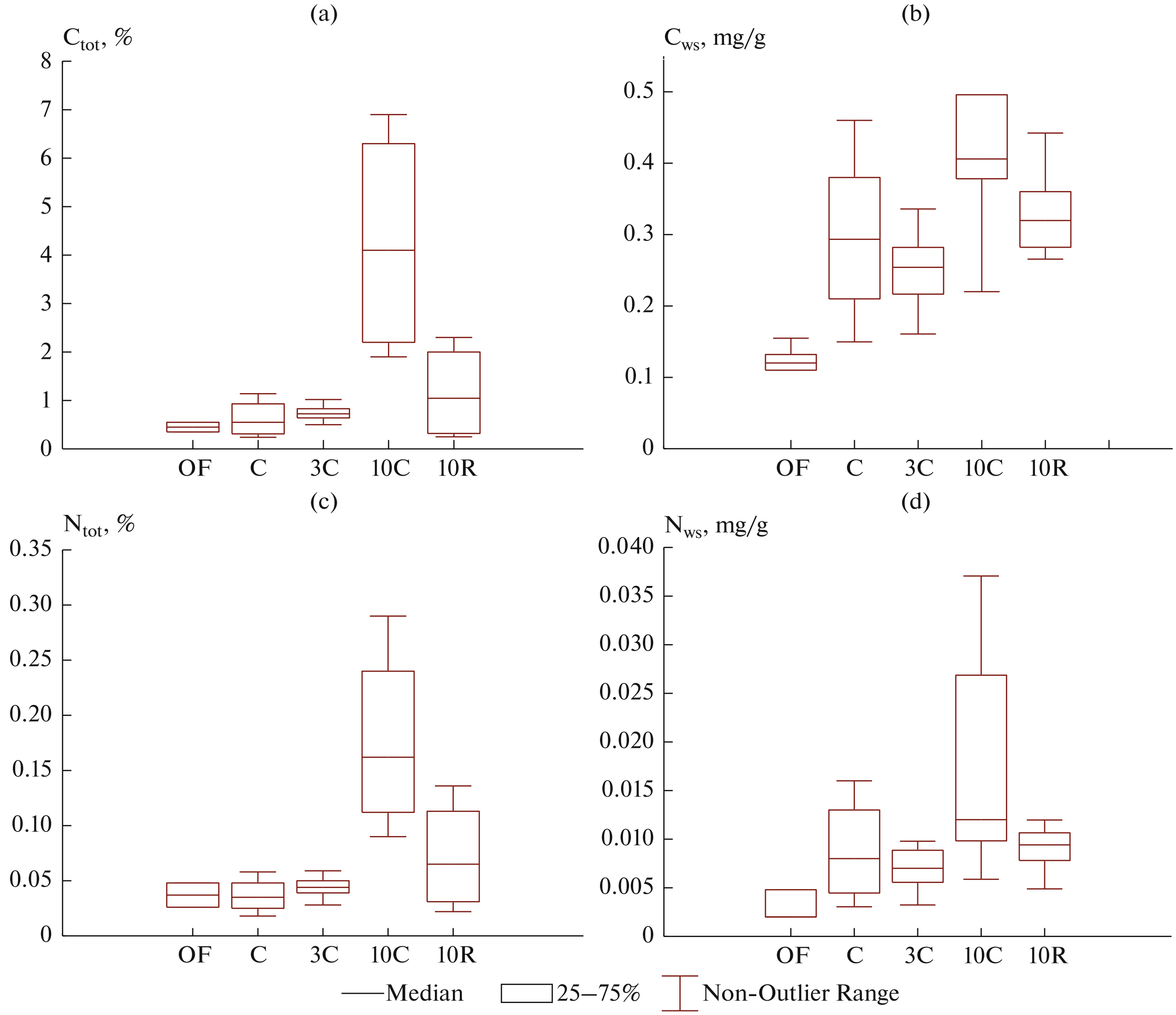

Fig. 3. Contents of (a_) C_{tot}, (b) C_{ws}, (c) N_{tot}, and (d) N_{ws} in the upper mineral horizons EL and TUR_{cwd} for 2021–2022; (±Δ) are the boundaries of absolute error interval at $P = 0.95$. For soil designations, see Fig. 2.

arranged in the following order: 0.45% (IF)—0.55% (P)—0.72% (3P)—4.1% (10P)— 1.05% (10R). Median values of the total nitrogen content show the similar pattern: 0.037% (IF)—0.035% (P)—0.044% (3P)—0.162% (10P)—0.065% (10R).

A significant increase in the carbon content was revealed in the upper turbated horizons TUR_{cwd} on the second year after logging: by 3–6 times as compared to the year of 2021 and by 4–14 times as compared to the initial values in the upper mineral horizon EL before logging. The nitrogen content in the upper mineral horizon of 10P soils increased by 2–4 times in compared to the previous year. Thus, the pool of buried organic matter may supposedly provide an important source of carbon that is likely to persist in skidding trail soils for a long time. As noted in [5], in mechanically disturbed soils of forest cutting sites, a large amount of carbon accumulates from slowly decomposing organic matter of large woody residues, which enriches the upper and underlying soil horizons with biophilic elements with time.

Water-soluble forms of carbon and nitrogen. The water-soluble fraction is an important constituent of organic matter; it is formed by litter filtrates, root exudates, and waste products of vital activity of soil fauna [32, 41, 50]. The C_{ws} distribution in the studied soils repeats to a great extent that of C_{tot}: it is also of regressive-accumulative type with a significantly lower C_{ws} content in mineral horizons than in litters. A strong relationship between the content of water-soluble carbon and soil organic carbon in long term [38] rather than in short term [73] is noted in publications.

Changes in water-soluble carbon and nitrogen in the cutting-strip soil. The soil at the original site before logging is characterized by the C_{ws} content of 1.68–

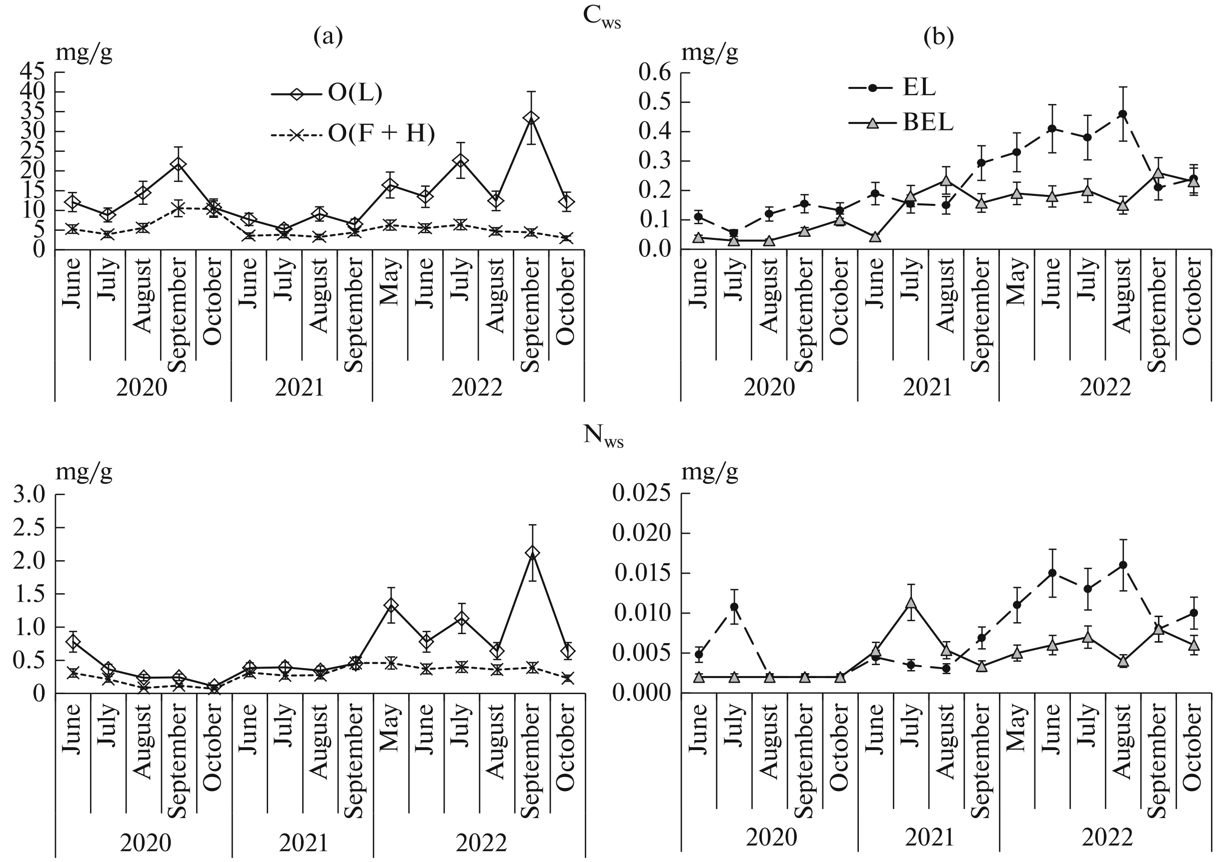

Fig. 4. Seasonal dynamics of C_{ws} and N_{ws} in the studied soils of the original forest (2020) and cutting strips (2021–2022) in (a) organic and (b) mineral horizons; (± Δ) are the boundaries of the absolute error interval at $P = 0.95$.

21.71 mg/g in the litter and 0.02–0.15 mg/g in the mineral horizon. The studies in assessing WSOM seasonal dynamics revealed an increase in the C_{ws} content in the litter in the fall season (Fig. 4). The maximum C_{ws} concentrations were noted for fresh litter subhorizons O(L); they varied in the following way during the monitoring period: 8.84 → 14.46 → 21.71 → 10.73 mg/g, which is probably due to the litter saturation with organic compounds coming with fresh needles and leaves in the growing season. The increasing dynamics of WSOM was noted for the medium- and well-decomposed litter subhorizons over time. This is most clearly manifested in the humified O(H) subhorizon. The C_{ws} content increased from 1.68 mg/g in July to 10.62 mg/g in October, which is due to the organic matter humification and the subhorizon saturation with rainwater rich in organic substances in the fall. Mineral horizons are specified by much lower content of water-soluble substances. Similar to the litter horizons, the content of water-soluble carbon rises in the upper eluvial horizon from July to September and falls in October. This is probably due to the start of rainy season and leaching of organic compounds from organic horizons into the upper mineral horizons. As noted in publications, WSOM concentration in soil is controlled by several factors, including climate conditions [36, 51]. Precipitation can lead to releasing higher WSOM concentrations to soil solution [46].

In general, the results are comparable to those obtained previously for a similar soil of a green moss spruce forest developing on loamy soils in well-drained landscapes of the Komi Republic [5, 34]. The analysis of publications attests to the closeness of the data obtained (0.077 mg/g) to the world average C_{ws} concentration in a the upper 30-cm-thick soil layer (0.073–0.081) [26, 27, 58, 40].

The monitoring carried out during the field- work in 2021 permitted us to identify changes in the content of WSOM in the studied soils already in the first year after winter clear cutting. The carbon content C_{ws} ranged from 3.3 to 9.1 mg/g in the soil litter of the cutting plot, which is lower than before logging. In mineral horizons, the C_{ws} content varied from 0.04 to 0.29 mg/g, which exceeds in general the initial values before logging. The WSOM distribution in the soil profiles remained similar to the background one, i.e., of the regressive-accumulative type. A tendency for an increase in the WSOM carbon content in the mineral horizons in the fall months was noted. The maximum

C_{ws} content in the EL horizon was observed in October (0.29 mg/g), which was likely due to the increase in precipitation and intensified migration of organic substances at the beginning of the fall. In addition, already in the first year after logging, a change in the TC content was observed in mineral horizons. In July and August, the carbon content in the upper eluvial horizon was lower than in the BEL horizon. This was not observed before cutting.

In the second year after cutting, a significant increase in the content of water-soluble carbon was revealed both in the organic and mineral horizons of the soil in the cutting strips as compared to the previous periods. In particular, this is true for the upper mineral horizons, where the flow of organic substances from the litter horizons is observed. This is caused by leaching of water-soluble organic substances not associated with mineral substances, which permeate the upper mineral horizons of soil. The C_{ws} content in the eluvial horizon varies from 0.21 to 0.46 mg/g during the growing season, which thrice on average exceeds the background values. In the underlying mineral horizon BEL, the C_{ws} content was four times higher than the pre-logging values and ranged from 0.15 to 0.23 mg/g.

The content of water-soluble nitrogen is significantly lower than that of carbon, but it shows the same patterns (Fig. 4). For the soil of the background plot, its content in the litter varied from 0.07 to 0.37 mg/g in 2020. In 2021, the N_{ws} content in the organic horizon of the cutting-plot soil increased significantly from 0.32 to 0.46 mg/g. After two years, the increase in the content of water-soluble nitrogen went on to reach 0.23–2.12 mg/g. A high N_{ws} content was also found for mineral horizons in the cutting-strip soil after cutting. In the upper mineral horizon EL, the content of water-soluble nitrogen varied from 0.002 to 0.011 mg/g in the background soil; BEL horizon was characterized by a very low content of N_{ws} during the season, 0.002 ± 0.0004 mg/g.

The results obtained are similar to the data published in [60], in which a 1.4-times increase in the nitrogen content was found in organic horizons after clear cuttings. The authors associate this increase with soil disturbance, higher water inflow, accumulation of decomposing woody debris, and with intensifying microbial activity [28]. The N_{ws} content in soil litters may be probably considered to be a conventional diagnostic feature of clearcutting effect on the soil organic matter.

Changes in water-soluble forms of carbon and nitrogen in soils in skidding trail areas. The organic horizon was preserved, though transformed in the three-pass (3P) soil in the skidding trail area. The C_{ws} content was equal to 2.8–8.3 mg/g in the first year after cutting, which was comparable to that in the original soil before logging and in the cutting strips. However, the C_{ws} content decreased in the litter from July to September. Even the minimal pressing is likely to alter the organic matter distribution in the soil profile. Two years after logging, an increase in the C_{ws} content was revealed: from 8.3 to 21.7 mg/g in the O(L) subhorizon and from 2.8 to 4.2 mg/g in the O(F+H) subhorizon. The pattern of C_{ws} seasonal dynamics in the organic horizon shows its maximum accumulation (22.2 mg/g) in July 2022, i.e., two years after cutting (Fig. 5). In other months, similar results were obtained (4.7–11.8 mg/g); however, a trend to increasing the C_{ws} content in litter after cutting was observed. The C_{ws} content in the upper mineral horizon (EL) of 3P soil, on the contrary, increased from July to September ($0.10 \rightarrow 0.16 \rightarrow 0.27$ mg/g), although the values were close to those in the background and cutting plots. In the second year after logging, a general increase in the C_{ws} content was observed in the eluvial soil horizon (0.22–0.34 mg/g) as compared to that in the first year after logging (Fig. 5).

In the first year after forest cutting, the contents of N_{ws} in 3P soil grew in the organic horizon over time from July to September ($0.248 \rightarrow 0.312 \rightarrow 0.371$ mg/g), which was higher than the values in the original forest soil and close to those in cutting plot soil. This is especially pronounced in the fall months with high humidity. In the second year, the N_{ws} nitrogen content varied from 0.260 to 0.510 mg/g in the 3P organic horizon, which was higher than in the original area and in a year after cutting. In the upper mineral horizon, the water-soluble nitrogen content ranged from 0.003 mg/g in July to 0.010 mg/g in September 2021, in the first year after logging. The N_{ws} content also tended to increase from the summer to the fall months. Two years after cutting, the content of nitrogen in water-soluble compounds in the eluvial horizon of 3P soil, on the contrary, decreased from the spring to the fall (May to October) from 0.009 to 0.005 mg/g. In general, the N_{ws} content in the mineral horizons of 3P soil two years after cutting was close to that in the original soil.

A significant increase in the contents of carbon and nitrogen of water-soluble substances was shown in the upper turbated soil horizons of ten passes (Figs. 3b and 3d). In addition, 1–10% increase in the C_{ws} share from the total organic carbon was observed in the mineral horizons of skidding trail soils with ten passes as compared to those with three passes. For 10P soil, C_{ws} gradually increased from 0.22 in July to 0.44 mg/g in September in the first year after cutting. Two years later, the content of water-soluble carbon increased significantly in the turbated horizon TUR_{cwd} varying from 0.38 to 1.15 mg/g. The maximum values were found in June (1.15 mg/g) and August 2022 (0.78 mg/g). In the 10P soil, the C_{ws} content was equal to 0.13–0.31 mg/g in the first year after cutting. In the second year after cutting, its content varied from 0.27 to 0.44 mg/g, which was generally

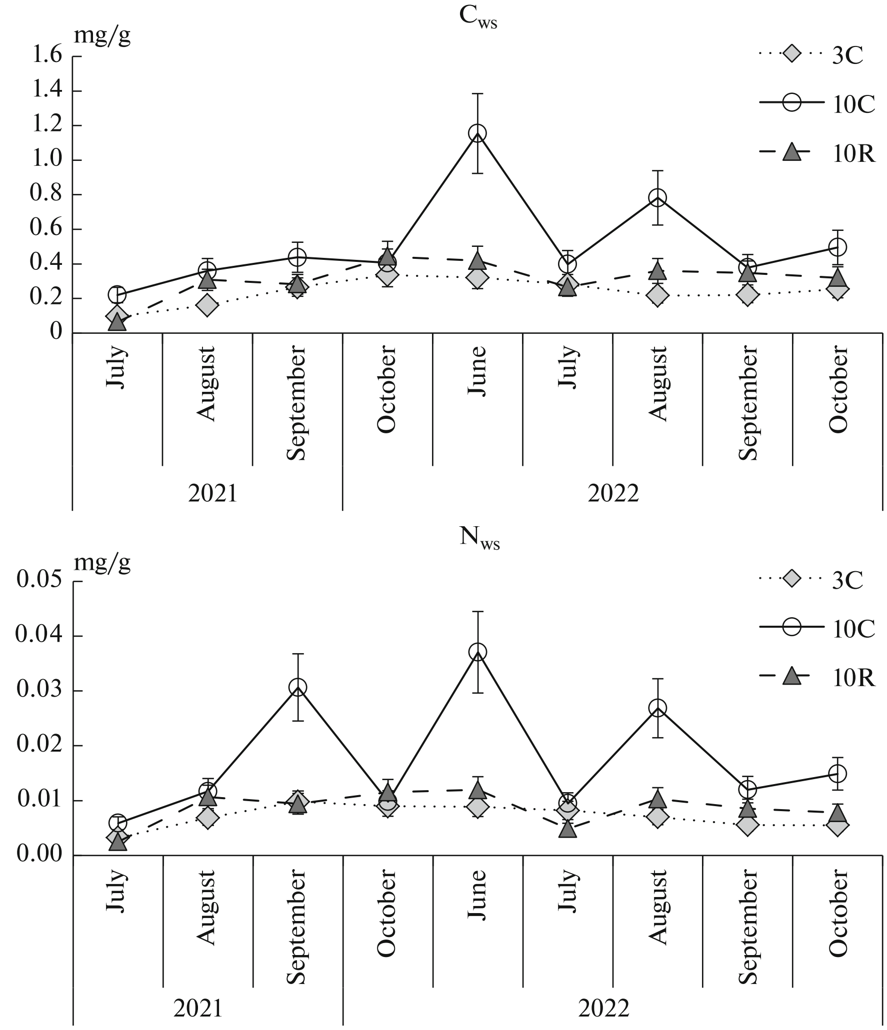

Fig. 5. Seasonal dynamics of C_{ws} and N_{ws} in the upper mineral horizons of soils of skidding trails (2021–2022); ($\pm \Delta$) are the boundaries of the absolute error interval at $P = 0.95$. For soil designations, see Fig. 2.

higher than in the first year after cutting, but appears to be similar to the results obtained for soils in other technological zones of the logging area.

In the turbated horizon of the skidding trail s with ten passes 10P, the water-soluble nitrogen content varied from 0.006 to 0.031 mg/g in the first year after clearcutting (Fig. 5). The trend to an increase in the N_{ws} content from the summer to the fall months was preserved. In the 10P soil, the nitrogen content was 0.003–0.011 mg/g in the first year. In the second year after logging, the N_{ws} content in the upper turbated soil horizon 10P was unevenly distributed by months, ranging from 0.010 to 0.037 mg/g. The maximum N_{ws} concentrations were in June and August 2022. For reclaimed 10R soil, the N_{ws} value had a more even seasonal distribution in the second year after felling. The C_{ws} carbon content was 0.005–0.012 mg/g two years after cutting, which was close to the value of one year after cutting (0.003–0.011 mg/g), but it was lower than in the 10P soil due to the completely absent organic horizon, which largely controls the composition and properties of organic substances [53].

Our study showed that the amount of plant falloff decreases sharply after clearcutting; this leads to a decrease in the content of water-soluble substances, as noted in the first year after cutting, despite the additional supply of logging residues. Some authors point out a lowering export of WSOM from logging sites [35]. A rising content of water-soluble organic substances in the litter and mineral horizons is probably due to the beginning of decomposition of woody residues and the colonization of the cleared area by herbaceous plants, which was observed in the second year after clearcutting. The increasing content of water-soluble forms of carbon and nitrogen in the upper mineral horizons of soils in skidding trail areas with different technogenic loads results from mixing of mineral and litter horizons and the input of additional organic matter with logging residues. As noted in publications, the increase in the WSOM content lasts for 2–10 years after clear cutting [52, 55]; then, it gradually decreases, which some authors associate with the stabilization of soil organic matter [31, 52, 60].

There is a large number of works aimed at finding relationships between the concentrations of water-soluble carbon and nitrogen compounds depending on climatic zones and type of vegetation [11, 29, 39]. Numerous studies have been carried out on the WSOM content dependence on temperature and humidity [29]. The availability of dissolved organic matter in soil also depends on its interaction with mineral components [63]. The particle-size distribution (the content of physical clay and clay fractions), water retention capacity, porosity and infiltration rate, which affect the soil sorption capacity, are important [62]. The content of aluminum and iron hydroxides, which appear to be one of the most important WSOM adsorbents, is an important index [44]. An interesting and important fact is that WSOM is a substratum for soil microorganisms, and it also affects the characteristics of microbial biomass carbon and microbial respiration [40, 70, 71]. Therefore, the specific features of WSOM and its impact on the microbiological parameters require further study [72].

Labile water-soluble carbon fractions are even more sensitive to soil disturbance than the total SOM pool [61]. Some authors point out the positive experience in using WSOM as an index of environmental changes in water and marine science and propose using its changes and trends in soil science [45]. The work [69] shows the WSOM concentration to respond sensitively to changes in land use and management, such as conversion of forests to agricultural systems.

CONCLUSIONS

As a result of investigating the effect of clear cutting on the content of carbon, nitrogen, and their water-soluble forms, it was found that even the minimal impact of wheeled logging equipment changes the distribution of these substances in the soil profiles. A significant increase in the C_{tot} and N_{tot} content was revealed in the upper turbated horizons of the studied soils. Similarly, the content of water-soluble forms of carbon and nitrogen increased to exceed the initial values in all the technological logging zones, which was due to the additional supply of logging residues to the surface and their decomposition.

A significant increase in the SOM content in the soil profile after clear cutting of forests allows us to conclude that this parameter is important for the study of changes in soil organic matter under the impact of various anthropogenic and natural factors. The content of C_{ws} and N_{ws} is of key importance, since it differs significantly from the initial values. It is acute to proceed with the scientific research of water-soluble carbon and nitrogen compounds and their changes as a result of natural and anthropogenic factors; the current study should serve as the basis for the further research.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

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

CONFLICT OF INTEREST

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

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