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Estimating of Carbon and Nitrogen Content in Forest Ecosystems in the Background Areas of the Russian Arctic (Murmansk Region)

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Abstract: In this study, we made an estimate of the carbon and nitrogen content in the undisturbed terrestrial ecosystems in the northern taiga zone of Russia's Murmansk region. The goal of this study was to examine the carbon and nitrogen dynamics in atmospheric fallout, assimilating organs of coniferous trees *(Picea obovata* and *Pinus sylvestris)*, needle litter, soils, and soil water. The objects of our research were the most common dwarf shrub-green moss spruce forests and lichen-dwarf shrub pine forests of the boreal zone. The study was carried out on permanent plots between 1999 and 2020. Long-term dynamics of carbon concentrations in snow demonstrated a trend towards increasing carbon concentrations in forested and treeless areas of Murmansk region. It was shown that in representative spruce and pine forests, the concentrations and atmospheric fallout of carbon compounds and carbon leaching with soil water were higher below the tree crowns, compared to between the crowns. In soil water, a decrease was found in carbon leaching with the soil profile depth. For soils, the highest carbon concentrations were found in the organic and illuvial soil horizons. The main soil sinks of carbon and nitrogen in northern taiga forests were found to be located in the organic soil horizon below the crowns. In northern taiga forests, the carbon content of living *Picea obovata* and *Pinus sylvestris* needles and *Pinus sylvestris* needle litter had minor variability; no significant interbiogeocoenotic and age differences were found. We found that the nitrogen content in brown needles and needle litter was significantly lower compared to photosynthetically active needles.

Keywords: northern taiga forests; atmospheric fallout; soils; *Picea obovata; Pinus sylvestris;* carbon; nitrogen; Arctic

1. Introduction

Presently, close attention, both internationally and nationally, is paid to assessing the contribution of terrestrial ecosystems to the regulation of carbon cycles, which indicates the need to collect data on the carbon content and stocks in various climatic zones and in various ecosystems.

Murmansk region is the northernmost region of European Russia, located north of the Arctic Circle and completely with in the Russian Arctic. Climate change has a significant impact on the natural environment of the Arctic. Forest ecosystems are exposed to multiple stress agents, being a combination of natural and anthropogenic agents.

Northern taiga forests are characterized by low productivity and low forest stand heights with a minor amount of undergrowth. The low productivity of the forest ecosystems at the northern forest line is due to a combination of low temperatures and a short growing season [1].

Soil factors largely control the direction of metabolic processes in biogeocoenoses and the productivity of phytocoenoses and determine the productivity of soil biota [2]. The controlling factors of soil-forming processes in the Far North are low ambient temperatures, abundance of precipitation combined with low evaporation, and low ash content of plant litter [3–5].

Conifer litter is one of the most important factors in the biogeochemical cycles of forest ecosystems, acting as a source of organic carbon and mineral nutrients that become available to biota as a result of decomposition and mineralization. Litter quantity and quality are influenced by both climate [6] and the composition of plant communities, age of dominant plants, etc. [7,8].

Carbon is the main component of atmospheric precipitation and originates from both biogenic and anthropogenic sources. The transfer of organic carbon from the atmosphere to the soil surface occurs in the form of wet (through precipitation) and dry (by deposition of particles and gases on the surface) deposition. Field studies of carbon fluxes in precipitation are relatively rare, in part because organic matter concentrations in the precipitation and the associated atmospheric deposition rates are not typically measured by large-scale monitoring networks [9,10]. Thus, quantitatively estimating the supply of carbon with atmospheric deposition into forest ecosystems is an important component of biogeochemical studies.

Most soil chemical reactions take place in the soil solution, which also plays a vital role in soil formation, plant nutrition, and the activity of soil biota [11,12]. The soil solution acts as the link between the solid phase of the soil and the roots of plants, since all nutrients, as well as potentially toxic substances, enter the roots through this pathway. In this connection, the soil solution chemistry can serve as an indicator of the impact of atmospheric pollution and other stress factors on forest ecosystems. Dissolved organic matter (DOM) in soils plays an important role in the biogeochemical carbon, nitrogen, and phosphorus cycles, soil formation and pollutant transport. The most important sources of DOM in soils are litter and humus [13]. Despite ongoing research, knowledge about the formation of DOM in soils and its response to changes in the natural environment and climate is still limited [13–17]. Long-term studies of DOM transport in soils and its removal from the soil layer are few in Russia [1,18–21]. More research is needed into the dynamics of DOM in soils of different nature zones and under different types of land use. In addition, when studying carbon and nitrogen cycles, a coupled analysis of various components of forest ecosystems (atmospheric fallout, soils, soil water, phytomass, and mortmass) is important, taking into account the intra- and interbiogeocoenotic vegetation cover mosaics.

The goal of this study is to estimate the content of carbon and nitrogen in the main components (atmospheric fallout, assimilating organs of woody plants, soils, litter) of northern taiga forests in the background areas of the Russian Arctic, specifically in Murmansk region.

2. Materials and Methods

We studied dwarf shrub-green moss spruce forests and lichen-shrub pine forests dominant in the boreal zone undisturbed (background) areas of Russia's Murmansk region. Long-term field research was carried out in 1999-2020 on three permanent monitoring plots (PMPs) by the Institute of Industrial Ecology Problems of the North KSC RAN (Figure 1). The plots are typical of the regional background areas in the study area and meet all the criteria for control plots as recommended by international programs [22]. The following components of forest ecosystems were studied: atmospheric fallout, soils and soil water, living (photosynthetically active) needles, and *Picea obovata* Ledeb. and*Pinus sylvestris* L. needle litter.

Pine forest soils are represented by illuvial-ferruginous podzols (Rustic Podzols, WRB), spruce forest soils – by illuvial-humus podzols (Carbic Podzols, WRB) [23,24] with the characteristic profile O–E –BHF (BF, BH) –C and demonstrate various degrees of soil moisture. Rustic Podzols are found under shrub, shrub-lichen, and lichen pine forests in drier locations, while Carbic Podzols are common in more humid locations [25]. The soils of the northern taiga forests of Murmansk region feature a shallow organic horizon and limited organic matter content, mineral horizons poor in nitrogen and humus, and are typically acidic. Organic matter plays an important role in the formation of the soil profile of Al-Fe-humus podzols. The organic horizon is mainly composed of organic remains. It contains at least half of all organic matter in these soils [26]. Mineral horizons differ in organic matter content. The illuvial horizon within the soil mineral profile is the horizon of maximum humus accumulation, while the overlying podzolic horizon contains less humus.

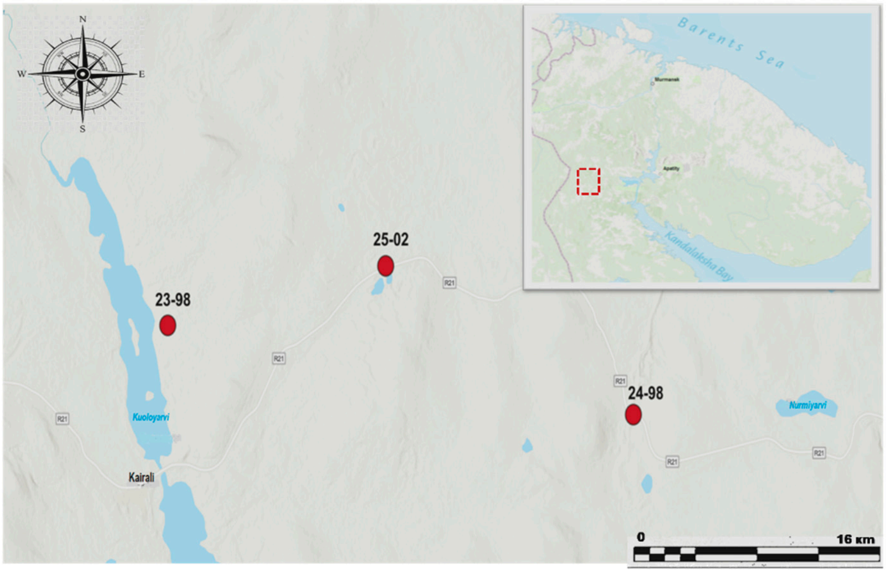

Figure 1. Location map of the study area: 23-98 – lichen-green moss-shrub pine forest, 25-02 – lichen-shrub pine forest, 24-98 – dwarf shrub-green moss spruce forest.

Snow, rainwater, and soil water samples were collected annually (1999-2020).

Snow cores were collected using a plastic core sampler over the entire depth of the snow pack to the soil surface annually before the onset of snowmelt (usually in the first week of April). Collection was carried out below the tree crowns, between the crowns, and in treeless (open) spaces in triplicate.

Rainwater was collected using precipitation funnels (five below the crowns, five between the crowns, four in open areas), composed of a plastic pipe with a funnel. A plastic bag is placed inside the pipe, secured with a cap. To prevent the ingress of plant litter, insects, and other particles, the surface of the pipe was covered with a removable fine mesh made of synthetic material before securing it with a cap.

Soil water was sampled using Derome gravity lysimeters [27] (12 pcs. per PMP), located at different depths in accordance with the soil profile (organogenic A0, eluvial E+B, illuvial BC/C) and taking into account the mosaic structure of the biogeocoeonosis (under the crowns and between the crowns in different parcels) [28].

During field sampling, the volume of rain and soil water accumulated in the funnels and lysimeters over a monthly period was measured using plastic measuring cups. Lysimetric and rainwater samples were collected monthly from May to October.

Soil and live *Piceaobovata* and *Pinussylvestris* needles were collected in five folds at the end of the growing season once every five to seven years. Soil samples were collected at the end of the growing season (August) in the dominant parcels below and between the crowns. In spruce forest, the dominant parcel was shrub-green moss, while in pine forest, it was lichen-shrub. Samples were collected according to soil horizons: litter/organic horizon (OL, OF, OH), eluvial horizon (E), illuvial horizon (BHF), and bedrock (C). Soil samples were dried at room temperature and then sieved. Fine soil fraction (< 1.0 mm) was subjected to analytical processing. Tree needle samples were collected from the upper third of the crown. In the laboratory, spruce and pine needles were sorted by age (current year needles, annual and perennial needles).

Pinussylvestris needle litter was collected in a lichen-green moss-shrub pine forest below the crowns and between the crowns. Conical funnels for collecting needle litter were installed at the PMPs (six between the crowns, six below the crowns). In pine forests, needle litter was collected twice annually – in June and October.

Chemical analytical studies of the samples were carried out at the Physicochemical Analysis Resource Sharing Center at the Institute of Industrial Ecology Problems of the North KSC RAN. Water samples were filtered through a blue-ribbon filter paper. Carbon was measured by

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chromatometry or permanganatometry, depending on the concentration. Total nitrogen (TN) and nitrogen (N) were determined using the Kjeldahl method [29]. For soil water, the concentration of mineral nitrogen was calculated as the sum of nitrate and ammonia nitrogen in mg/l. The carbon content (Corg) in soil, needle, and litter samples was determined by the Tyurin method.

Descriptive statistics and trends for estimating the content of carbon and nitrogen in atmospheric fallout, soil and soil water, living needles, and needle litter were obtained in Microsoft Excel 2019. To compare the composition of various components of ecosystems in different biogeocoenoses and compare the content of carbon and nitrogen below and between the crowns, the Mann-Whitney U test and the Statistica 13.3 software were used.

3. Results and discussion

3.1. Carbon and nitrogen in the atmospheric fallout

Winter atmospheric fallout is confined to a period of biological dormancy. In boreal forests, the duration of annual snow cover is 100-200 days, which determines the significant role of precipitation in the form of snow in biogeochemical cycles. Atmospheric fallout in the form of rain plays an important role in chemical cycles and the functioning of forest ecosystems. The chemical composition of rainfall changes significantly after passing through the forest canopy. During this interaction, physicochemical reactions occur, leading to changes in the water acidity and the concentrations of most elements [30].

In spruce and pine forests, the concentrations of carbon and nitrogen in snow and rainwaterbelow the crownswere significantly ($p<0.05$) higher than between the crowns and in the open spaces (Table 1). Increased concentrations of carbon and nitrogen below the crowns indicate the wash-off and leaching of elemental compounds from plant tissues. Carbon concentrations in the snow below and between the crowns in lichen-shrub pine forests were up to two times higher ($p<0.05$) compared tospruce forests, lichen-shrub pine forests, and treeless areas. In rainwater, carbon concentrations below the crowns in spruce forests were up to two times higher ($p<0.05$) than in pine forests. Increased carbon concentrations in rainfall below the crowns in spruce forests are attributable to the thicker spruce canopy compared to pine. Between the crowns in pine forests, nitrogen concentrations are higher (up to 1.1 times) compared to spruce forests.

Table 1. Concentrations of carbon (C) and nitrogen (TN) in the atmospheric fallout, 1999-2020.

PMP	BGC type	Element	Snow		Rain	
			Below	Between	Below	Between
23-98	lichen-green moss-shrub pine forest	C	2.69	1.17	57.88	4.66
			0.32	0.15	2.68	0.34
		TN	ND	ND	0.51	0.23
					0.18	0.03
25-02	lichen-shrub pine forest	C	4.39	2.85	45.06	4.92
			0.43	0.36	1.79	0.26
		TN	ND	ND	0.53	0.43
					0.09	0.11
24-98	spruce forest lichen-shrub-green moss	C	3.30	1.57	91.32	5.37
			0.38	0.19	5.39	0.30
		TN	ND	ND	0.47	0.36
					0.04	0.07
Treeless area	wetland		Treeless area			
		C	2.65		4.27	

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		0.58	0.33
	TN	ND	0.32
			0.07

Notes: below – below the crowns, between – between the crowns. Here and in Tables 2–5: numerator is the mean, denominator is the standard error. ND – not determined.

Long-term dynamics of carbon concentrations in the atmospheric fallout in pine and spruce forests demonstrated significant variability, both below and between the crowns. In the rainwater below the crowns in the lichen-green moss-shrub pine forest, a trend ($R^2 = 0.78$) was found in 1999-2009 of decreasing carbon concentrations – from77 to 61 mg/l. In 2013-2020, in the rainwater in the treeless area, a trend ($R^2 = 0.83$) was found of increasing carbon concentrations –from 3.2 to 5.52 mg/l. In snow, in recent years, there was a trend of increasing carbon concentrations in the treeless area, as well as below the crowns in the dwarf shrub-green moss spruce forest and both below and between the crown in the lichen-shrub pine forest (Figure 2). An increase in carbon concentrations in snow, clearly observable below the crowns, may be associated with an increase in the number of thaw days in Murmansk region [31].

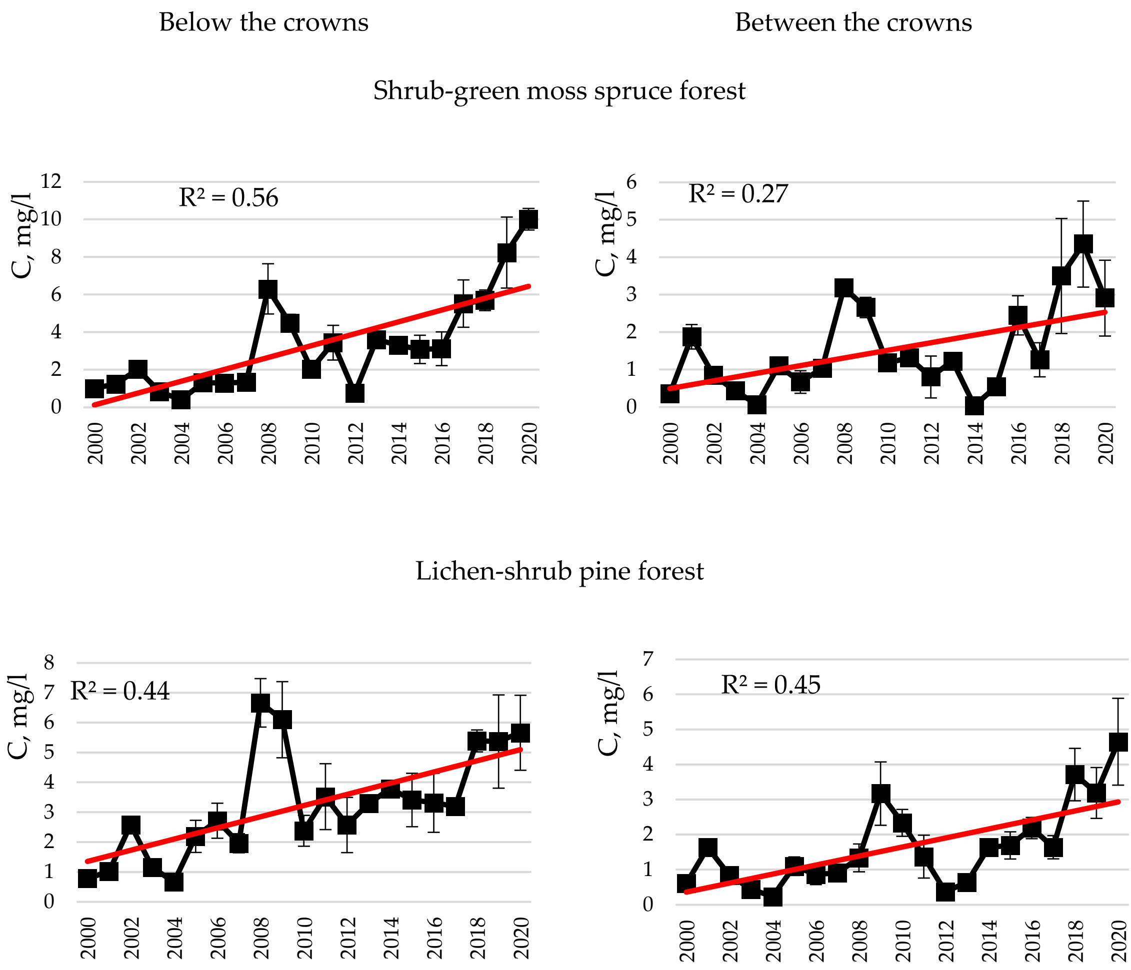

Figure 2. Carbon concentration in the snow water in the spruce and pine forests.

Carbon deposition with snow below and between the crowns does not differ significantly, despite the 1.2-1.3 times higher precipitation between the crowns. Below the crowns of spruce forests, average annual carbon deposition for the period from 1999 to 2020 was 0.09 g/m²/year, between the crowns 0.07 g/m²/year, in pine forests – 0.07 and 0.06 g/m²/year, respectively. Carbon deposition with

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rain in spruce and pine forests was significantly higher below the crowns than between the crowns; the amount of precipitation between the crowns was significantly (up to 2 times) higher than below the crowns. In spruce forests, carbon deposition below the crowns and nitrogen deposition between and below the crowns was higher than in pine forests (Figure 3).

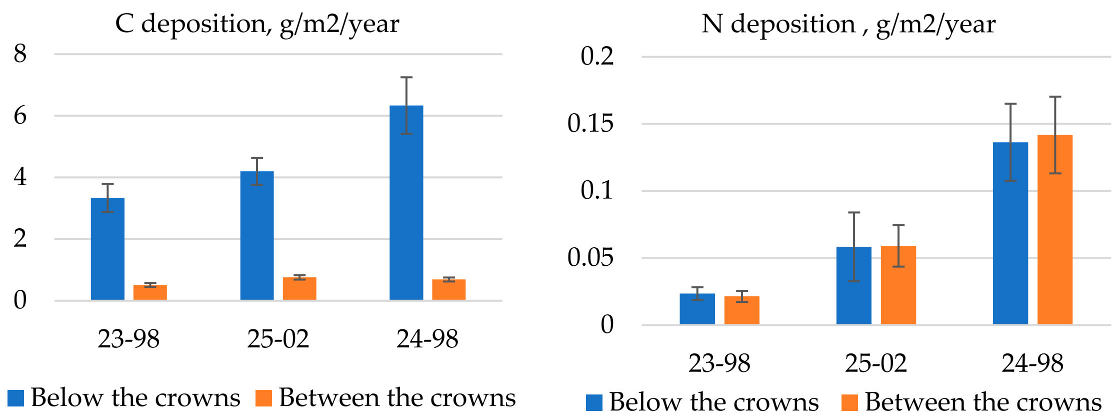

Figure 3. Carbon (C) and nitrogen (TN) deposition with rain in spruce and pine forests.

3.2. Carbon and nitrogen in the soil

Soil cover, as the most conservative component of an ecosystem, determines its condition and sustainability and plays an important role in the formation, maintenance, and preservation of biological diversity [32]. The organic horizon of the studied forest soils, in which the bulk of plant root systems is found and active mineralization processes occur, was characterized by a high content of nutrients [1].

The carbon content in the organic soil horizon in the spruce and pine forests varied from 12 to 57%. In mineral horizons, a significant decrease in carbon content was found compared to the organic horizon. Mineral horizons were found to be rich in organic matter. The illuvial horizon (B) of the mineral profile was found to be the horizon with the highest carbon accumulation (0.40-1.62%), while the podzolic horizon (E) contained less carbon (0.21–0.72%). The carbon content in the C horizon decreased with the soil profile depth (below the B horizon) to 0.06–0.67% (C horizon).

The carbon content in the soils of pine and spruce forests below and between the crowns was mostly comparable. Significant differences were found only in the E horizon ($p<0.05$) in the lichen-shrub pine forest, where the carbon content between the crowns was higher than below the crowns.

The carbon content in the OF and OH horizons of the pine forest was higher ($p<0.05$) than in the spruce forest. In the B horizon, to the contrary, a higher carbon content was observed in the spruce forest than in the pine forest (Table 2).

Table 2. Soil carbon (C) and nitrogen (N) in 2005-2020, %.

PMP	BGC type	Soil horizon	OL	OF	OH	E	BH	C horizon
		Below the crowns						
23-98	Lichen-green moss-shrub pine forest	C	50.92 1.42	49.74 1.58	42.56 2.51	0.37 0.07	0.72 0.05	ND
		N	1.08 0.03	1.17 0.05	0.82 0.09	0.02 0.003	0.05 0.003	ND
		C/N	47.48	42.85	55.49	15.43	16.27	ND

			1.48	1.63	5.69	1.84	1.44	
		Between the crowns						
		C	48.94	49.86	44.53	0.43	0.71	0.32
			1.40	1.60	1.60	0.10	0.10	0.09
		N	0.79	1.01	0.95	0.02	0.05	0.02
			0.07	0.05	0.03	0.003	0.01	0.004
		C/N	63.34	50.13	46.92	16.09	15.89	16.72
			4.26	2.76	1.87	2.18	1.42	6.01
25-02	Lichen-shrub pine forest	Below the crowns						
		C	49.17	46.74	40.71	0.25	0.52	ND
			1.72	3.00	3.64	0.04	0.08	
		N	1.13	1.15	0.96	0.02	0.03	ND
			0.11	0.07	0.09	0.002	0.003	
		C/N	47.37	40.80	43.58	14.63	20.05	ND
			5.90	2.27	3.55	2.73	2.14	
		Between the crowns						
		C	49.88	46.23	39.97	0.46	0.83	0.24
			1.64	2.04	3.04	0.08	0.18	0.04
		N	0.90	1.11	0.89	0.02	0.04	0.01
			0.04	0.10	0.08	0.003	0.01	0.001
		C/N	56.13	44.11	46.01	22.71	20.68	18.58
			3.82	5.65	4.42	4.83	2.41	5.06
24-98	dwarf shrub-green moss spruce forest	Below the crowns						
		C	47.57	43.48	34.35	0.33	1.15	ND
			1.43	1.47	4.76	0.06	0.16	
		N	1.52	1.69	1.29	0.03	0.07	ND
			0.07	0.05	0.20	0.002	0.01	
		C/N	31.79	25.91	27.15	12.37	16.73	ND
			2.28	1.04	0.78	2.21	0.95	
		Between the crowns						
		C	49.89	41.47	16.41	0.34	1.37	0.39
			1.47	1.55	3.90	0.05	0.43	0.03
		N	1.68	1.12	0.62	0.02	0.07	0.03
			0.06	0.13	0.09	0.001	0.02	0.004
		C/N	29.89	39.74	25.99	16.24	17.55	15.92
			1.15	5.03	3.25	2.70	1.31	2.06

The nitrogen content is closely dependent on the carbon content, because almost all the nitrogen in the soil is found in the organic matter. The nitrogen content in the organic soil horizon in the pine and spruce forest was 5.2–13.3 and 4.7–18.7 g/kg, respectively. The illuvial horizon (B) of the mineral profile was the horizon with the highest nitrogen accumulation (0.29–0.89 g/kg). In the podzolic horizon, compared to the illuvial horizon, the nitrogen content was lower at 0.10–0.50 g/kg. With depth, the nitrogen content gradually decreased to 0.10–0.51 g/kg (C horizon). The organic matter of

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the northern taiga forest litter was depleted of nitrogen, with the C:N ratio typically exceeding 30. In pine forests, the C:N ratio is up to 60–82. The C:N ratio in the top horizons of the litter is largely controlled by the conditions of decomposition of plant residues (microbiological activity, differences in water and light regimes, etc.) [33]. In the mineral horizons, especially in the B horizon, the nitrogen content in organic matter increased, but insufficiently (C:N = 15–25).

In the pine forest, the nitrogen content below and between the crowns was comparable. In the spruce forest, the nitrogen content in the OF and OH horizons below the crowns was up to 1.4 times higher ($p < 0.05$) than between the crowns. The presence of intrabiogeocoentic differences in spruce forest is due to the structure of spruce crowns, in which connection this tree species has a stronger influence on the conditions below the crowns, compared to pine.

In the spruce forest, the nitrogen content below the crowns in all soil horizons and in the OL and C horizons between the crowns was significantly ($p<0.05$) higher than in the pine forest. This can be explained by the higher content of nitrogen compounds in the atmospheric fallout in spruce forests compared to pine forests.

In the E horizon below the crowns, the carbon content in the spruce forest was higher than in the lichen-shrub pine forest.

Carbon and nitrogen stocks in the soils of northern taiga forests showed intrabiogeocoentic differences. The bulk of soil carbon and nitrogen was concentrated below the crowns and varied from 2 to 18 t/ha and 0.015 to 0.624 t/ha, respectively. The lowest carbon and nitrogen stocks were found in the OL horizon, the highest in the OH horizon (Figure 4).

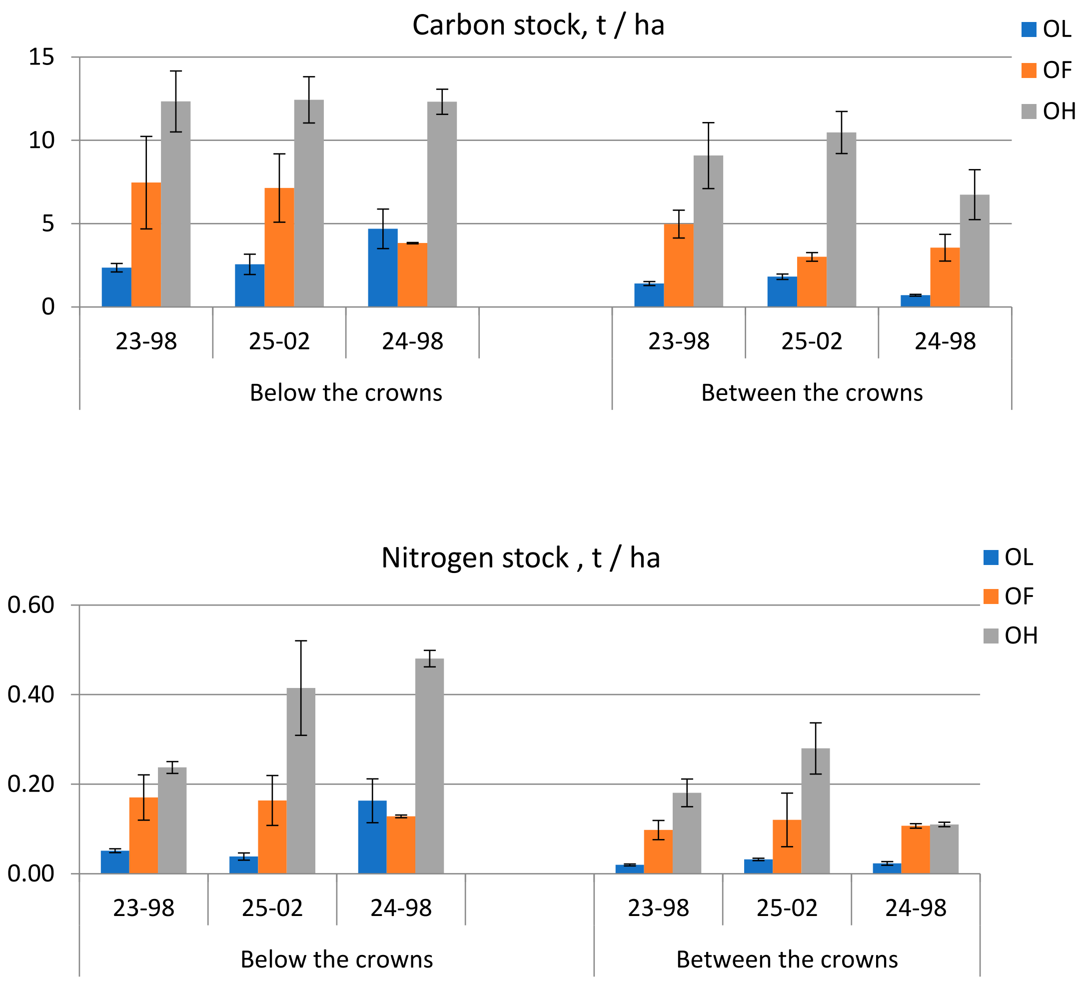

Figure 4. Carbon and nitrogen stocks in the organic soil horizon of northern taiga forests, t/ha.

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3.3. Carbon and nitrogen in the soil water

Soil solution is the most active soil phase. It is there that the vast majority of all chemical reactions in the soil occur. Water is the link in the system organisms-soil-rocks-atmosphere. Metabolism occurs mainly through the liquid phase, i.e., soil solution, ground and surface water [34].

Carbon concentrations in organic soil horizon water below the crowns in the spruce and pine forests were up to six times higher, in the eluvial soil horizon up to 3.5 times higher, in the illuvial horizon of spruce forest soils up to 2.5 times higher ($p < 0.05$) compared to between the crowns (Table 3).

Table 3. Carbon (C) and nitrogen (TN) in the soil water in 1999-2020, mg/l.

PMP	BGC type	Element	O	E+B	BC
23-98	lichen-green moss-shrub pine forest	Below			
		C	175.85 10.01	ND	ND
		TN	0.68 0.10		
		Between			
		C	36.69 1.54	16.87 5.38	ND
		TN	0.25 0.02	ND	
25-02	lichen-shrub pine forest	Below			
		C	82.75 4.17	50.34 1.77	27.12 2.66
		TN	0.65 0.07	0.41 0.06	0.41 0.12
		Between			
		C	43.89 2.83	31.85 1.39	29.70 2.01
		TN	0.67 0.06	0.41 0.05	0.31 0.04
24-98	shrub-green mossspruce forest	Below			
		C	84.92 4.63	52.34 5.44	23.64 2.75
		TN	0.87 0.15	0.36 0.04	0.25 0.04
		Between			
		C	47.47 2.70	45100 1.69	13.56 1.3
		TN	0.48 0.04	0.27 0.05	ND

Notes: O – organic soil horizon (3-5 cm), E+B (15-25 cm) – eluvial soil horizon, BC – illuvial soil horizon (30-40 cm).

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Soil Total nitrogen below the crowns of spruce and pine forests in the organic soil water and in the eluvial horizon water of spruce forests were higher than between the crowns. Increased concentrations of elements below the crowns indicate the wash-off and leaching of element compounds from the tissues of dominant woody plants. There was a significant decrease in carbon and nitrogen concentrations with the depth of the soil profile, both in spruce and pine.

Interbiogeocoenotic differences below the crowns demonstrate significant differences only in carbon concentrations in the organic soil horizon water: in the lichen-green moss-shrub pine forest, carbon concentrations were significantly higher (up to two times) than in the lichen-shrub-green moss spruce forest and the lichen-shrub pine forest. Between the crowns, carbon concentrations in the organic and mineral horizon water in the pine forest were, in most cases, significantly higher than in the spruce forest. This can be explained by the higher carbon content in the organic soil horizon below and between the crowns in the pine forest compared to spruce forest. However, it should be noted that between the crowns the concentration of carbon in the organic soil horizon water in the spruce forest was significantly higher than in the pine forest.

No significant interbiogeocoenotic differences in the concentration of nitrogen in the water below the crowns were found. In the water below the crowns in the lichen-shrub pine forest, the lowest nitrogen concentrations were observed, up to three times lower than in the lichen-green moss-shrub pine forest and in the dwarf shrub-green moss spruce forest.

The long-term carbon dynamics in the water of all soil horizons in the pine and spruce forest demonstrated significant variability. One can note a trend of increasing carbon concentrations in the water from the organic soil horizon and decreasing in the water from the mineral soil horizon below the crowns in the spruce forest in recent years (Figure 5).

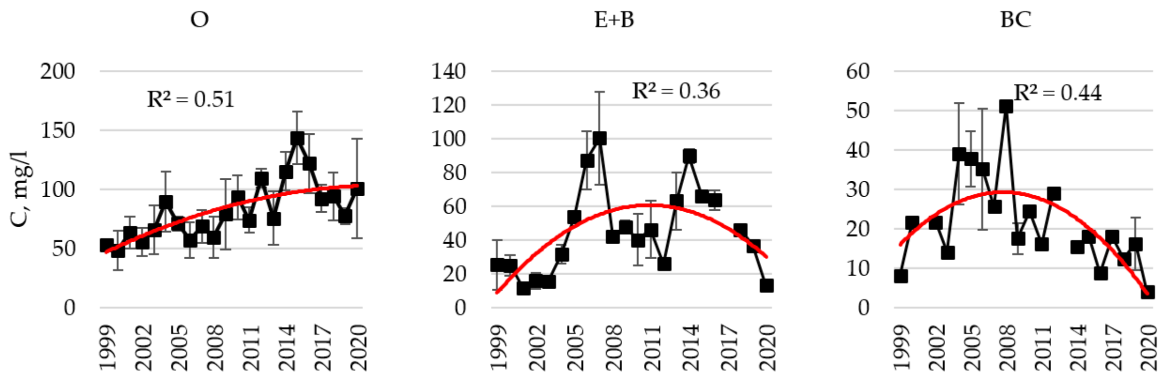

Figure 5. Carbon in the below-crown water in the spruce forest. O – organic horizon (3-5 cm), E+B (15-25 cm) – eluvial horizon, BC – illuvial soil horizon (30-40 cm).

The critical level of mineral nitrogen (0.2 mg/l) in the mineral horizon water was not exceeded, as a rule; in the organic horizon water, mineral nitrogen usually exceeded critical concentrations, which is especially typical of spruce biocenoses (Table 4).

It should be noted that when estimating the critical limits of mineral nitrogen concentrations proposed earlier [35], natural variation below the crowns could not be taken into account because lysimeters, according to ICP Forests methods, were installed between the crowns (this forest soil research practice is common).

We believe that for the normal development of trees in these conditions, the observed higher mineral nitrogen concentrations are not critical. No nutritional imbalance was detected by visual examination. Our data support the earlier findings presented in Lukina et al. [36].

Table 4. Mineral nitrogen in the soil water and critical nitrogen concentrations in the soil waters of different forest types/different tree species.

Nmin					Critical Nminconcentration limits		
PMP	Horizon	Below	Between	Between	Effect	N, mg/l	Types of woody plants
23-98	O	0.30 0.02	0.24 0.02	0.24 0.03	Nutrient imbalance	> 0.2 > 0.4	Coniferous forests Deciduous forests
25-02	O	0.35 0.02	0.35 0.03	0.42 0.03	Increased N leaching/N saturation	> 1	All types of forest
	E+B	0.29 0.02	0.37 0.09	0.26 0.02			
	BC	0.28 0.04	0.49 0.25	0.24 0.04	Reduction in fine root biomass/root length	> 3	All types of forest
24-98	O	0.58 0.04	0.42 0.03	0.38 0.03			
	E+B	0.27 0.03	0.24 0.03	0.28 0.07	Increased sensitivity to frost and fungal diseases	> 5	All types of forest
	BC	0.16 0.02	ND	ND			

The average annual removal of carbon and nitrogen with water from the organic and mineral soil horizons in 1999- 2020 below the crowns in the spruce and pine forests was significantly higher than between the crowns (Figure 6). Interbiogeocoenotic differences in the removal of carbon and nitrogen with soil water from organic and mineral horizons were similar to the reported differences in the concentrations of these elements.

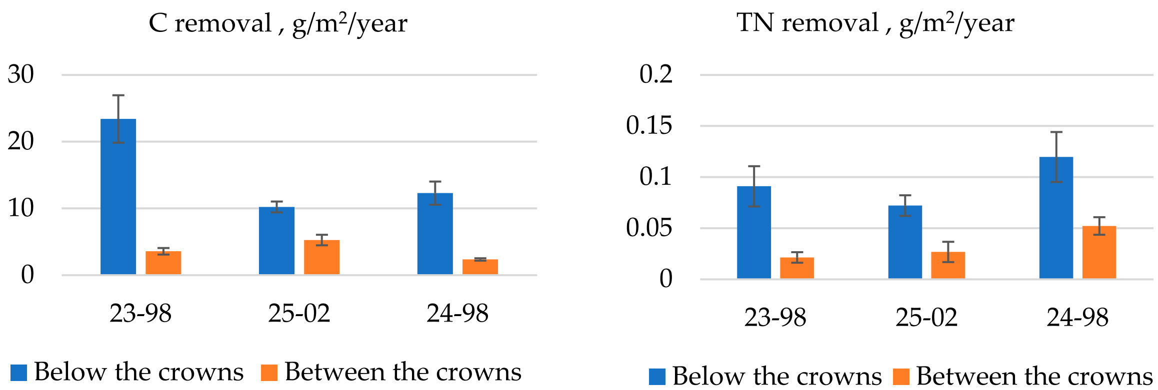

Figure 6. Removal of carbon and nitrogen with water from the organic soil horizon in the pine and spruce forest.

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3.4. Carbon and nitrogen in the living needles and litter

It was shown that the carbon content in *Piceaobovata*and *Pinussylvestris*needlesvariesbetween 41 and 68% (Table 5). As the needles age, the carbon content remains virtually unchanged. The explanation may lieinthe redistribution of carbon between various organs in favor of roots and, especially, shoots, where the carbon assimilated during photosynthesis is deposited. No significant interbiogeocoenotic differences in carbon content were found (Table 5).

The nitrogen content in the current year and perennial needles of the lichen-dwarf shrub pine forest was significantly ($p<0.05$) higher than in the spruce forest and lichen-green moss dwarf shrub pine forest. The nitrogen content in the currentyearneedles in the lichen-green moss shrub pine forest was up to three times higher than in perennial and brown needles, as well as in litter. In the lichen-shrub pine forest and in the shrub-green moss spruce forest, the nitrogen content in the current year needles was also higher than in perennial and brown needles.

Table 5. Carbon (C) and nitrogen (N) in the living needles and litter in 2005-2020, %.

PMP	BGC type	Element	Current year	1 year	Perennial needles	Brown needles	Litter
23-98	lichen-green moss-shrub pine forest	C	55.25	55.28	55.54	53.61	56.91
			0.97	1.01	1.56	1.05	0.77
		N	1.16	1.09	1.00	0.45	0.32
			0.04	0.04	0.04	0.02	0.02
25-02	lichen-shrub pine forest	C	51.71	56.24	55.01	56.28	ND
			1.57	1.61	1.20	0.80	
		N	1.30	1.14	1.09	0.41	ND
			0.04	0.03	0.03	0.01	
24-98	shrub-green mossspruce forest	C	53.83	52.45	53.32	ND	ND
			1.23	1.10	1.16		
		N	1.20	1.16	0.96	ND	ND
			0.03	0.04	0.03		

4. Conclusions

1. Carbon and nitrogen in snow and rainwater, as well as atmospheric fallout of these, were found to be higher below the crowns in spruce and pine forests than between the crowns, which is associated with the wash-off and leaching of elements from the tree crowns. In rainwater in spruce, carbon concentrations and deposition below the tree crowns were higher than in pine. Increased carbon concentrations in the rain depositionbelow the crowns in the spruce forest are attributable to a thicker spruce canopy compared to pine. The long-term dynamics of carbon concentrations in snow demonstrated a trend of increasing carbon concentrations in treeless areas, as well as below the crowns in the dwarf shrub-green moss spruce forest and both below and between the crowns in the lichen-shrub pine forest. An increase in carbon concentrations in snow, clearly expressed below the crowns, may be associated with an increase in the number of thaw days in Murmansk region.

2. In spruce and pine forests, a significant decrease was observed in the content of carbon and nitrogen in the soil's mineral horizons compared to the organic horizon. No significant intrabiogeocoenotic differences in carbon content were found in pine and spruce forest soils. The nitrogen content below the crowns in spruce and pine forests was typically higher than between the crowns. Interbiogeocoenotic differences in carbon content were weakly expressed; in the organic soil horizon, the carbon content was higher in pine compared to spruce, while in the mineral soil horizon, on the contrary, there was a higher carbon content in spruce compared to pine. The nitrogen content below the crowns and between the crowns in the organogenic and mineral soil horizons in the spruce forest was higher than in the pine forest. This can be explained by the higher content of nitrogen

compounds in the atmospheric fallout in spruce forests compared to pine. The main stocks of soil carbon and nitrogen in northern taiga forestsare concentrated below the crowns.

3. The concentrations of carbon and nitrogen in the soil water, as well as the removal of these, were typically higher below than between the crowns in the spruce and pine forests. Increased element concentrations in the soil water below the crowns indicate the washout and leaching of element compounds from the tissues of dominant woody plants. In the pine forest, carbon concentrations were usually higher than in the spruce forest, which can be explained by the high carbon content in the organic soil horizon below and between the crowns in the pine forest. The long-term dynamics of carbon concentrations in water from all soil horizons in pine and spruce forests was characterized by significant variability.

4. The carbon content in living *Picea obovata* and *Pinuss ylvestris*needles and *Pinussylvestris*needle litterhadminor variability; no significant interbiogeocoenotic and age differences were found. The nitrogen content in the current year needles was typically higher than in perennial needles and was significantly reduced in brown needles and needle litter.

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