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Taiga fire on Bolshoy Ushkany Island as a model case of forest soil transformation and potential source of eutrophication in Lake Baikal coastal zone

Vashukevich N.V.[1], Timoshkin O.A.[2]*, Samsonov D.P.[3], Kulikova N.N.[2], Levasheva M.V.[4], Lukhnev A.G.[2]

[1] *Ural State Agrarian University, 42 Karl Liebknecht Str., Ekaterinburg, 620075, Russia*
[2] *Limnological Institute of the Siberian Branch of the Russian Academy of Sciences, 3 Ulan-Batorskaya Str., Irkutsk, 664033, Russia,*
[3] *Research and Production Association (RPA) "Typhoon" Roshydromet, 4 Pobedy Str., Obninsk, 249038, Russia*
[4] *Irkutsk State University, 1 Karl Marks Str., Irkutsk, 664025, Russia*

ABSTRACT. The soils of a model site in Severnaya Bay, affected by fire in June 2015, on Bolshoy Ushkany Island (Lake Baikal) were studied. About 70% of the Island taiga burned. The bloom of cyanoprokaryotes in the coastal zone and their massive wash-ups were observed in this bay a year later, in summer 2016. When studying the soils at two points of observation (a high and a low-intensity fire), we focused on geochemically congugated soil profiles. Wildfire strongly affected top soil horizons (4 – 5 cm), entailing changes in charred roots biomass, soot, charcoal and structural aggregate stability. Migration and accumulation of total organic carbon (30 – 35 mg/g), N-NH4 (40 mg/kg), phosphates (104 mg/kg) detected at the foot of the slope, were 1.5 – 3 times higher than the content of these elements in the unburned soil. The slope migration of pyrogenic carbon was traced studying polycyclic aromatic hydrocarbons (PAHs). Retene, a marker of wood combustion, comprised 80-90% of PAHs. In the upper part of the slope, PAH was 270 ng/g, in the transit position – 47 ng/g. In the lower part, due to the accumulation of pyrogenic organic compounds, the content of PAH increased to 100 ng/g. Post-pyrogenic slope erosion was detected a year after the fire in Severnaya Bay. Biogenic migration and accumulation in the beach area (including interstitial water) can have consequences as a potential factor in the eutrophication of Lake Baikal coastal zone.

Keywords: taiga fires, pyrogenic soils, nutrients, polycyclic aromatic hydrocarbons, retene, Baikal, coastal zone eutrophication

1. Introduction

Ushkany Islands are a unique object in Baikal aquatorium. The archipelago consists of four islands that are peaks of the underwater Academic Ridge dividing the Northern and Middle basins of the Lake. Bolshoy Ushkany Island is the largest of them with the area of 9 km^2 and 216 m elevation over the water's edge (Lamakin, 1952; Efimova and Zuev, 2016). The nature uniqueness of the islands is provisioned by their isolation, geological and geomorphological features, specificity of climate. The Archipelago is the locus of local flora and fauna speciation (Kozhov, 1962; Timoshkin, 2001) known, first, as the largest natural shelter for Baikal seals. The islands house over 5–6 thousand of anthills (several dozen per hectare).

Visiting the territory of Ushkany Islands is strictly regulated by law according to its conservation status. However, substantial amounts of household waste were found on the beaches of Bolshoy Ushkany Island during last 4–5 years. Still, the background regime of the processes and components in the ecosystem has been preserved that predetermined our choice of this area as a model site for studying them in dynamics.

In June 2015 (Fig. S-1 in Supplemental electronic material), Bolshoy Ushkany Island suffered from wildfires presumably caused by a dry thunderstorm. In summer 2016, a research team headed by Prof. O.A. Timoshkin registered abundant algal blooms and massive wash-ups of blue-green algae in the nearshore area of Severnaya Bay on Bolshoy Ushkany Island (Timoshkin, 2020). The hydrochemical parameters of the nearshore water appeared normal, whereas the interstitial water samples collected from the pits in the splash zone showed elevated concentrations of main nutrients (Dr. I.V. Tomberg (LIN SB RAS) pers. comm.). There was intense forest fire in the close vicinity with the shore of Severnaya Bay in June 2015.

*Corresponding author.
E-mail address: timole.turgenevo@gmail.com (O.A. Timoshkin)

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It is noteworthy that the data on the post-pyrogenic stocks of biogenic and abiogenic elements in the nearshore waters of Baikal is quite limited. This study would be a valuable contribution to our understanding of the temporal and structural dynamics of Baikal ecosystem: it is a matter of common knowledge that Baikal forests supply over 90% of the water inflow and they are vitally important for the production and preservation of the pure lake water (Lebedev et al., 1979).

This work was aimed at investigating geochemically conjugated soil profiles, a slope catena, their ecological state and assessing potential impacts of fire-derived slope erosion on migration of nutrients into Baikal splash/coastal zone.

2. Materials and methods

We focused on the soils at a model site selected in 2017 and based on field observations of environmental consequences of forest fires in Severnaya Bay. The site consisted of two observation points (PO1 and PO2), their location scheme is presented in Fig. 1. Fig. S-2 (see the ESM) shows the bay water's edge when the profiles were created.

A morphological description of the geochemically conjugated soil profiles, a slope catena, including 19 samples collected for mesomorphological and physicochemical analyses, has been undertaken at these observation sites. Five samples were collected from some soil profiles to analyze polycyclic aromatic hydrocarbons (PAHs) as typical markers of pyrogenic processes, especially, in the coniferous forests.

Physicochemical soil properties were studied at an Experimental Test Facility «Irkutsk Interregional Veterinary Laboratory» (Accreditation Certificate № ROSS RU. 0001.21ПО90, 05.11.14). The analyses were performed according to the following standards: pH of the water extract – RF State Standard (GOST 26423-85); organic matter content – RF State Standard (GOST 26213-91); mobile compounds of phosphorus – RF State Standard (GOST 26209-91), exchangeable ammonium – RF State Standard (GOST 26489-85).

Polycyclic aromatic hydrocarbons (PAHs) were identified by extracting them from the sample by n-hexagene, subsequent clean up in columns with silica gel, gas chromatography-mass spectrometry (GC/MS) analysis and quantitative analysis of individual PAHs. The analyses were performed by a gas chromatograph mass spectrometer Agilent 7200 Q-TOF (R > 9000).

3. Results and discussion

Investigations of fire-derived impacts on soils were carried out during several decades in different regions of Russia and abroad. The information available in scientific reports enables us to frame the scope of principal problems of understanding the post-pyrogenic processes in soils, as well as the effects of fires on ecosystems (Certini, 1999; Neary et al., 1999; Mataix-Solera et al., 2011; Dymov et al., 2018).

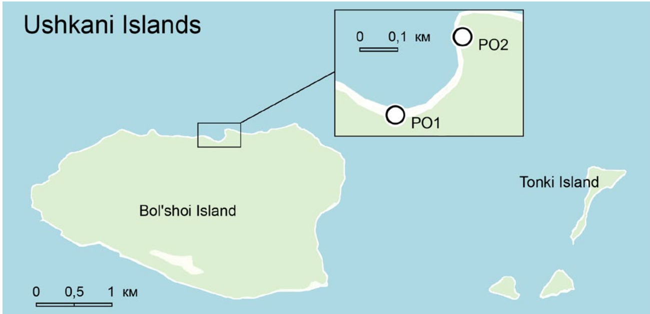

Fig.1. Schematic presentation of observation points (PO) in Severnaya Bay of Bolshoy Ushkany Island, 2017.

It was found out that burned uppermost layers and the underlayers formed a thin pyrogenic horizon with specific physicochemical properties and biological turnover, quite different from analogous types of the native soils. Accumulation and migration of pyrogenesis products (ash, charcoals, soot, water-soluble compounds) can be traced along to the soil profile. Many researchers showed evidence of pH increase, growth of exchangeable bases, carbon and amorphous iron in soils, and the nitrogen amount decrease. Thermal effects cause degradation of physical and water-physical properties of soils. Aliphatic and aromatic compounds, formed as a result of organics burning as well as mineral constituents of ash containing multivalent cations, are involved in hydrophobization and cementation of topsoil horizons. This leads to decrease of the water infiltration abilities and increasing topsoil susceptibility to runoff. Fires increase the potential of erosional processes dozens of times reducing thickness of the fertile soil layer, taking away, first of all, various suspended and dissolved biogenic substances which later might become the source of chemical and bacterial contamination deteriorating the water quality in river and lake ecosystems.

Principal issues of fire-derived impacts on the structure and functions of aquatic ecosystems were also in the focus of recent scientific reports (Smith et al., 2011; Bixby et al., 2015). The main concern of this work was large-scale studies of several dozens of boreal lakes in two provinces of Canada (Quebec and Northern Alberta) after wildfires.

Fires in lake watersheds noticeably changed the biogeochemical parameters of water. It was reported that total phosphorus concentration in lakes grew two times and more, 1.2–1.5 times was the concentration of dissolved organic carbon, total nitrogen, nitrate and ammonium increased as well in two years after burning of boggy dark- coniferous forests of northern Alberta. Surveys of Quebec Lake territories two years after forest fires revealed 2–3 times growth of the average concentrations of total phosphorus, 60 times of mean concentrations of nitrates and dissolved organic carbon. Nutrient enrichment entailed significant increase of the phytoplankton biomass observed for three years and was the greatest in first two post-fire years. A small post-fire growth of limnoplankton biomass (seston > 53 μm) was registered only during first two years (Carignan et al., 2000; Lamontagne et al., 2000; McEachern et al., 2000; Pinel-Alloul et al., 2002).

Forest burning in Baikal basin stands in sharp contrast to the surrounding territories. It is related to climate aridity and dominance of fire hazardous light-coniferous forest plants.

The results of long-term studies of post-pyrogenic (fire-affected) transformations of soils in the mountainous zone of Pribaikalye are reported by Yu.N. Krasnoshchekov et al. (2012; 2014; 2018). Negatively impacted by fires are podzols and podburs of cedar forests and grey-humus soils in light coniferous forests. Stocks, quantitative fractional composition of the forest litter and their water-physical characteristics changed. Erosion at the burned sites was generally regarded as sheet flow and rill runoff. Liquid and solid surface runoff were quantified at the burnt sites depending on the slope steepness. It was pointed out that soil erosion products from burned sites made the situation of Lake Baikal water contamination still more complicated.

Bolshoy Ushkany Island is a unique model for monitoring terrestrial ecosystems in Pribaikalye (Molozhnikov, 2014). Permanent test sites and the soil quadrates were established there by V.N. Molozhnikov in 1964 and 1978. Meanwhile, to set the periodicity of the forest fire events a dendrochronological approach was made use of. It was found out that in 1977 one third of the Island burned down, in 1937 the whole territory was entirely burned. Until 1937, fires occurred on the Island in 1907, 1857 and 1812 (Molozhnikov, 2014). Major post-pyrogenic changes were registered in larch forests, whereas pine forests remained less affected.

Thus, last geobotanical and pedological surveys of Bolshoy Ushkany Island carried out in 1969 reported that it took 24 years for the ecosystem to recover after the latest fire.

Assessment of the fire-derived slope erosion in Severnaya Bay on Bolshoy Ushkany Island was based on 3-years observations of the geochemically conjugated soil profiles at PO1 and PO2. The researchers traced the behavior of biogenic elements reaching the beach, higher concentrations of which were seen in the interstitial waters of the zone. Characteristic horizons differentiation (Ostrikova, 2008) and soil mesomorphology is presented below.

The illustrations of general characteristics of individual profiles, morphology and mesomorphology of the horizons are illustrated in the Supplement, the Figures are marked by a number and letter “S”.

3.1. Observation point 1 (PO1), 53°51′45.4″ N, 108° 38′6.6″ E

Soil sections were laid from bottom to top along the north-facing slope (general view of the slope, Fig. S-3). The slope descends to the beach (Fig. S-4A) where interstitial water samples were collected (Fig. S-4B). A general view of geochemically conjugated soil profiles, a slope catena 1–3 at PO1 is presented in Fig. S-5.

Soil section 1. *Coarse-humus, illuvial humus (mobile humus?).* Soil type: *Raw-humic, illuvial-humic* (Ostrikova, 2008) (and *Mollic Leptosols Eutric* according to the World Reference Base for Soil Resources 2014 (IUSS Working Group WRB, 2015) (Fig. S-6). Lower part of the slope (terrace scarp base).

AOpir (0–5 cm) – dark brown, sandy clay loam, upper part of the horizon poorly mixed, entomofauna activities have pronounced effect on the lower soil horizon, inclusions of many charred plants remain (wood + grass), clean mineral grains larger in the upper part of horizon (Fig. S-7), numerous inclusions of iron- and carbonate-coated grus (Fig. S-8), biota present (Collembola, mites, algae).

AO (5–20 cm) – loose, greyish brown, raw humus (mor), poorly decomposed organics, finely cloudy-powdery structure, a positive reaction of 10% HCl indicates the presence of soluble carbonates around the roots, highly abundant mesofauna and other biota (mites, Collembola, many mushroom hyphae), inclusions of large clean mineral grains (marble disintegration products) and multi-size grus with iron and humus coatings.

Chi (20–50 cm) – greyish brown sandy loam, plentiful pebbles, single roots, binocular examination shows pebbles and mineral grains colored by mobile organic matter (Fig. S-9), light spots in the horizon are evidence of weak eluviation (downward or sloping intra-soil migration).

Cca (from 50 cm) – whitish yellow sandy loam rich in multi-sized pebbles, effervescence from 10% HCl.

Soil section 2. *Coarse humus, residual carbonate.* Soil type: *Raw-humic, residual-calcareous* (and *Mollic Leptosols Eutric*) (Fig. S-10). Middle part of slope (terrace scarp).

AOpir (0–3 cm) – dark brown, sandy clay loam, unstable finely clody structure with many charred plants remains and large mineral grains.

AO (3–25 cm) – greyish brown, sandy clay loam, finely clody -powdery, aggregates with distinct mineral grains on surface (weak eluviation), raw humus (mor type), inclusions of numerous poorly decomposed plant residues, plentiful fresh roots, multi-sized grus.

Cca (25–50 cm) – yellowish grey coarse sand with large pebbles (3–7 cm), effervescence from 10% HCl treatment, solitary roots.

Soil section 3. *Dark-humus burozem, residual-carbonate.* Soil type: *Brownzems, residual-calcareous* and (and *Haplic Cambisols Dystric*). (Fig. S-11). Upper part of terrace scarp (near edge).

Opir (0–0.5 cm) – very thin (after burning) forest litter, dark grey, loose, extremely dry consisting of charred poorly decomposed tree litter, abundant inclusions of charcoal, mesofauna absent, noticeable density change.

AUpir (0.5–4 cm) – dark grey with reddish tint, very dry, sandy clay loam, with densely matted grass roots, large quantities of fine charcoals, mineral grains became ochreous under high temperatures (burning) (Fig. S-12), clody structure became very unstable, mesofauna absent.

AU (4–10 cm) – brownish-dark grey, dry, lower part of horizon slightly more humid, sandy clay loam, finely clody-powdery, humus type- moder, inclusions of fresh and slightly charred plant residues, mineral grains larger in size then those in the upper horizons and covered by iron-humus and iron coatings, single specimens of mesofauna.

BMca (10–30 cm) – yellowish-brown, humus spots around charcoal inclusions (traces of earlier pyrogenic impact), medium loamy, lumpy-nuciform structure of one level, some ferrous-clayey material acts as a cementing agent for mineral grains (Fig. S-13), grus inclusions, single roots, weak 10% HCl reaction, possible translocation of carbonates from the underlying horizon.

BMCca (30–40 cm) – brownish-dark grey with inclusions of significant quantities of rounded pebbles, solitary roots, possible presence of a buried pyrogenic horizon, carbonate effervesce when treated by 10% HCl.

Cca (from 40 cm) – well-rounded fine (1–3 cm) pebbles with greyish-yellow coarse sand, solitary roots, vigorous 10% HCl reaction.

Soil section 4. *Dark-humus burozem, residual-carbonate.* Soil type*: Brownzems, residual-calcareous and (and Haplic Cambisols Dystric)*. (Fig. S-16). A gentle 9–10 m decline from the top of the shore terrace scarp. Moderate wood stand damage, one side of tree stems burned, active recovery of plant cover in burned areas (Fig. S-14), many burned anthills (Fig. S-15). Negligible post-fire soil degradation, upper part of forest litter slightly affected (Fig. S-17). In further comparisons, this profile was used as a background model.

Opir (0–1 cm) – forest dark grey, loose, very dry consisting of poorly decomposed charred needle litter, branches, cones, roots, mesofauna absent, marked density transition in the underlying horizon.

AUpir (1–4 cm) – dark grey, sandy clay loam, clody, many inclusions of charcoal, grus covered with ferric and ferric-humus coatings, mesofauna absent, local effervescence in numerous light-coloured spots, marked colour transition.

AU (4–20 cm) – greyish-dark brown, unevenly coloured, alternating darker and lighter segments (Fig. S-18), dry, sandy clay loam, clody grained, moder, inclusions of charred plant residues, charcoal, fresh tree roots, grus, solitary mesofauna specimens.

BM (20–35 cm) – yellowish brown, medium clay loam, clody nuciform, soil structure of two-three levels, inclusions of grus and solitary root's weak reaction after 10% HCl treatment.

BMCca (35–55 cm) – brownish-dark grey, medium clay loam, inclusions of large quantities of rounded pebbles and small charcoal fragments (evidence of previous forest fires), solitary roots, medium effervescence after 10% HCl application.

3.2. Observation point 2 (PO2), 53°51′49″ N, 108°38′12.5″ E

Shore terrace. Fire intensity is higher than at PO1: many fallen trees and brushwood heaps. The forest litter burned out, minimal grass cover recovery, extensive growth of mosses on surfaces (Fig. S-19). Anthills burnt out completely (Fig. S-20). Washout of the destructed surface, translocation of pyrogenetic products and mineral stocks from soil horizons across the slope at the edge of the terrace scarp (Fig. S-21).

On the beach at the foot of the slope, a selection of water was carried out (Fig. S-22).

Soil section 5. *Dark-humus burozem, residual-carbonate.* Soil type: *Brownzems, residual-calcareous* and (and *Haplic Cambisols Dystric*). (Fig. S-23). A flat segment of terrace near the edge. The soil section was later referred to as maximally affected by fire events.

AUpir (1–3 cm) – brownish-grey, light-medium clay loam with unstable lumps, the horizon composed essentially of carbonaceous dust and soot with a thin coating of fine, well washed mineral grains where moss cover is formed (Fig. S-24), solitary plant remains, mesofauna absent, marked transition in colour.

AU (3–8 cm) – greyish-dark brown, unevenly coloured, alternating darker and lighter segments, inclusions of fine clean mineral grains, solitary plant remains.

BM (8–20 cm) – brownish-yellow, medium clay loam, clody nuciform structure of 2–3 levels, ferrous and clay material acts as a cohesive agent for mineral grains, grus inclusions, solitary roots, weak 10% HCl reaction.

BMCca (below 20 cm) – brownish-dark grey with many inclusions of rounded pebbles, medium 10% HCl reaction.

Overall, forest fires caused significant changes in the topsoil (4–5 cm) on Bolshoy Ushkany Island, such as charred or burnt plant remains, absence of biota (in general, it is abundant in O and AO horizons), formation of reddish fire-derived coatings on mineral grains, destruction of soils. Presence of grus and dust particles in the upper horizons of soil profiles 1–4 allows researchers to diagnose genesis of aeolian-deluvial deposits.

Since a quantitative assessment of biogenic elements (C, $N–NH_4$, $P–P_2O_5$) in post-pyrogenic soils based on water body eutrophication is rather complicated, we made an attempt to compare their content at 1, 2, 3 PO1, 5 PO2 profiles and 4 PO1 (reference soil) the least affected by fire.

Soils analogous to those available prior to burning were extremely hard to find because the territory of the Island exposed to the last fire 2015 was very large. In order to compare current stocks of organic carbon in the soils of the Island affected by fires to different extents (Fig. 2) and assess our choice of soil section 4 (Brownzems, residual-calcareous) as reference soil, we used the data on organic carbon content (COC) in humus horizons of sod-calcareouses soils (Soil classification of 1977) published by M.K. Shimaraeva (1969). It is worthy of note that COC accumulation (12–13%) in sod-calcareouses soils and profile 4 was generally similar. Apparently, slightly depressed location of the site on a flat terrace-like surface provided partial intactness of the forest floor and safeguarded the underlying humus from complete burning down.

Similar soil at the edge of the terrace (section 3) selected by the mesomorphological characteristics was somewhat drier. It presumably evidences of a greater thermal effect and accumulation of carbon 1–2% higher due to the presence of fine dispersed organic matter (soot particles).

Brownzems, residual-calcareous soil of the section 5 (PO 2) was subjected to most intense burning. The content of organic carbon in the upper AYpir horizon was the lowest (approximately 7%) among the soils studied, and in terms of mesomorphology the horizon was referred to as "carbonaceous dusty with soot". Carbon appeared to be a most sensitive indicator of the biogenic element migrations. Fig. 3 presents downslope distribution of carbon in soil horizons at PO1. It demonstrates two-fold increase in the middle-lower part of the slope (sections 2 and 1, Raw-humus). Analysis of the lowest soil part showed formation of an illuvial humus horizon Chi with carbon content similar to that in the upper Brownzems, residual-calcareous (section 3) at the edge of the slope (approximately 13%).

Analysis of the polycyclic aromatic hydrocarbon (PAH) content in soils at PO1 allowed us to trace migrations of post-pyrogenic matter in the slope. The plots in Fig. 4 show their total amount as well as Retene content (1-methyl-7-isopropyl phenanthrene), comprising 80–90% of the PAHs detected there. Retene is known as a coniferous wood combustion marker (Ramdahl, 1983).

Whereas total PAH sum constituted approximately 270 ng/g in the upper part of the slope, then their content decrease to 47 ng/g due to their intense removal in the transitional profile 2, and in the lower part (section 1) the content of PAHs rose actually two times (exceeding 100 ng/g) as a result of organic matter accumulation. Previously reported 2–9-fold increase of the total amount of PAHs in fire-affected soils was generally related to accumulation (formation) of light bi- and tri-nuclear PAHs capable of migrating via vertical and lateral fluxes into geochemically subordinate landscapes. Mobility of PAHs depended on organic matter solubility growing with higher pH values (Dymov et al., 2015; Rey-Salgueiro et al., 2018).

According to the literature data, two N forms prevalent in the soils, N– NH_4 and N–$N0_3$, were most affected by burning. Combustion caused rapid oxidation of the soil organic matter and organic N escape releasing N–NH_4. Ammonium nitrogen was partially concentrated in the mineral matrix of soil. Ash produced by burning presumably contained significant amount of N–NH_4 (DeBano et al., 1998). Meta analyses of 87 research surveys undertaken and published during 1955–1999 allowed quantitative assessment of forest fire effects on ammonium nitrogen in soils. It was shown that NH_4^+ pool increased approximately two times after fires and then gradually decreased during a year reaching pre-fire values (Wan et al., 2001). As previously mentioned, content of ammonium nitrogen was generally higher under a layer in the heated but not burnt forest floor. Summing up, the largely exposed to fire, more heated soils, showed higher N–NH_4 content (Aref'eva and Kolesnikov, 1964).

The above-mentioned patterns are shown in the plots describing distribution of ammonium nitrogen in the soil studied (Fig. 5A). Maximal content of N–

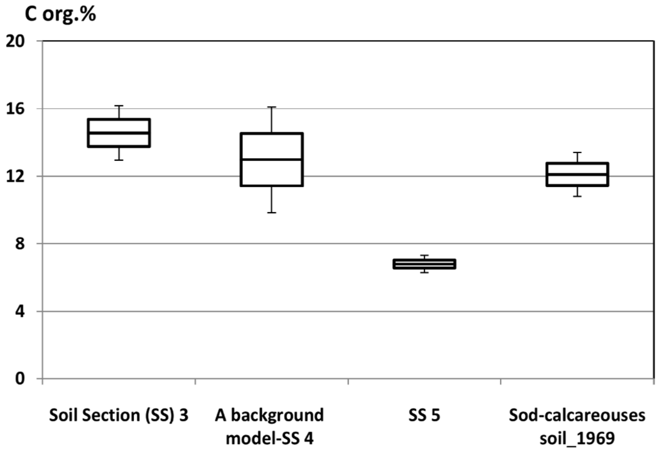

Fig.2. Content of organic carbon in soil horizons on Bolshoy Ushkany Island.

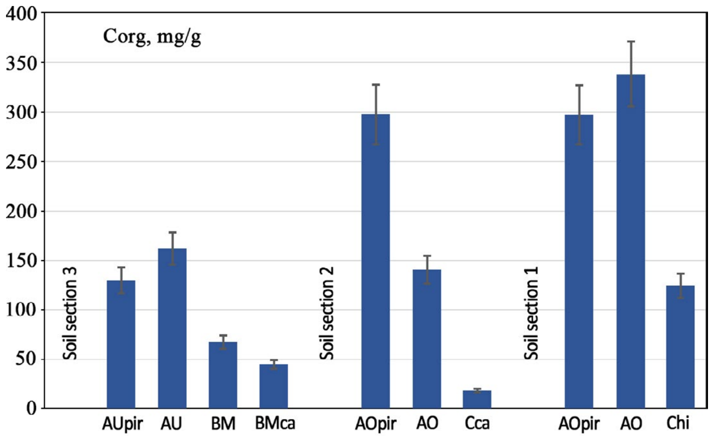

Fig.3. Content of organic carbon in soils at PO1 on Bolshoy Ushkany Island. Hereinafter: SS – soil section; AUpir – soil horizon name; PO – observation point).

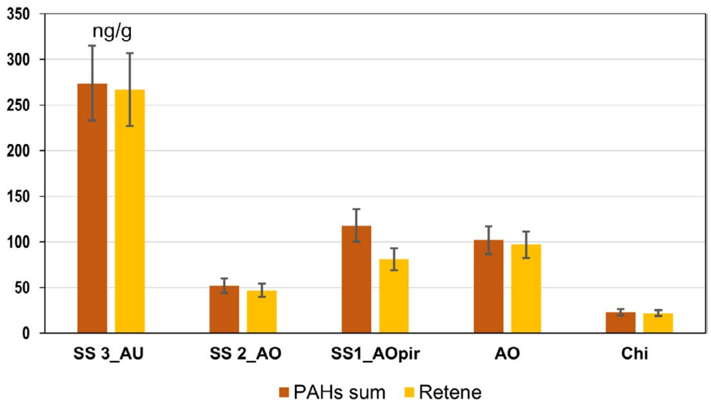

Fig.4. Distribution of PAHs in soils at PO1, Bolshoy Ushkany Island.

NH_4 (55–57 mg/kg) exceeds two times its level in a conditionally reference soil of section 4. It was registered in section 5 at PO2 where the fire was most severe as well as in humus horizon of section 3 where, as previously mentioned, we observed relative drying of mineral matter and the effect of burning was medium to low. Researchers also observed migrations of ammonium nitrogen along the slope sections (3-1), its content in the accumulative part being only 10 mg/kg less than its maximum. If we extrapolate a year back using publications already discussed, the average N–NH_4 content would reach about 100–120 mg/kg.

Mobility of the third biogenic element, phosphorus (Fig. 5B) to a greater extend is related to the actual pH of soils, generally attributed to neutral-slightly alkaline. As a whole, all pyrogenic horizons are characterized by an increased phosphorus release due to the presence of ash with higher alkalinity. Its maximal content was again confined to the accumulative part of catena PO1 (104 mg/kg) that largely exceeded analogous values in AU horizon of the reference soil in section 4.

4. Summary

After very severe fires the soil surface is usually covered by a so-called “black” or pyrogenic carbon. They are small-sized products of combustion (coal dust, soot), individual organic compounds produced by fire and capable of migrating with water. Pyrogenic carbon was found to be more mobile when subjected to erosion than the non-pyrogenic carbon. Pyrogenic organic carbon enrichment of eroded sediments compared to unaffected soils was 2.3 (Rumpel et al., 2006).

Accumulation of biogenic elements (C, N, P) in the lower part of the slope at PO1 falls approximately within the same limits (1.5–2 times). These data provide evidence of a relationship between higher biogenic concentrations in the interstitial zone of Severnaya Bay on Bolshoy Ushkany Island and fires in 2015. Thus, migration of biogenic elements from soils of burned nearshore taiga forest and their accumulation in beach zones (including interstitial water) should be considered as a potential and important factor contributing to eutrophication of the nearshore zone of Lake Baikal. Taking into account, that the forest fire intensity around Baikal coasts has been very high in 2015–2016, the present investigations on the isolated Bolshoy Ushkany Island may serve as a model case study for the questions of the general impact of this factor on the ecological condition of the coastal zone of the entire Lake.

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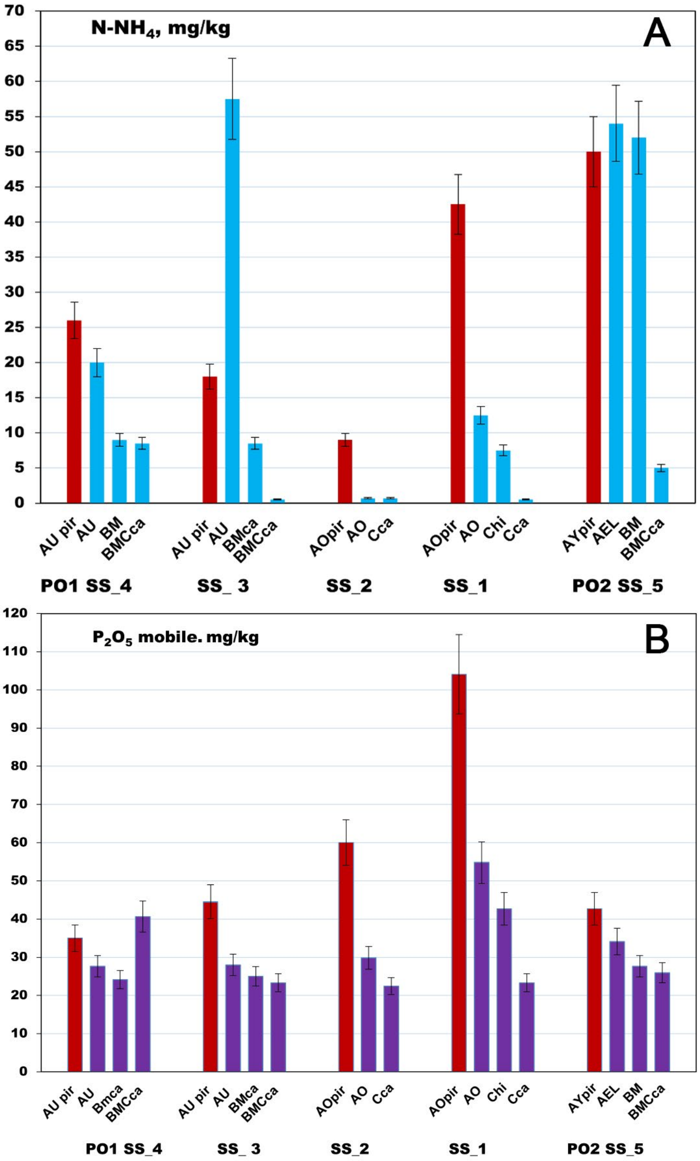

Fig.5. Content of ammonium nitrogen (A) and mobile phosphorus (B) in soils at PO1, PO2 on Bolshoy Ushkany Island, mg/kg.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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