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RESEARCH IN THE BAIKAL WATERSHED

Hydrochemical and Microbiological Characteristics of Bog Ecosystems on the Isthmus of Svyatoi Nos Peninsula (Lake Baikal)

V. V. Khakhinov[a], B. B. Namsaraev[b], G. S-S. Dorzhieva[c], and S. P. Buryukhaev[b]

[a] *Baikal Institute of Nature Management, Siberian Branch, Russian Academy of Sciences, Ulan-Ude, Russia*
[b] *Institute of General and Experimental Biology, Siberian Branch, Russian Academy of Sciences, Ulan-Ude, Russia*
[c] *Buryat State University, Ulan-Ude, Russia*
e-mail: khakhinov@mail.ru

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Abstract—Presented are the results from hydrochemical and microbiological investigations into Arangatui bog ecosystems on the isthmus of Svyatoi Nos Peninsula on the shores of Lake Baikal. The formation features of bog waters as a result of a rise in the lake's water level.

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INTRODUCTION

Bogs with an accumulative character of exchange of matter and energy possess one of the main carbon pools of biosphere. The role played by bogs in the formation of the atmospheric gas composition is commonly known: the vegetation cover of the bog ecosystems across the globe releases into the atmosphere up to $1.6*10^8$ t of oxygen per year; furthermore, the process involves the formation of greenhouse gases, such as CO_2 and CH_4. The source for gases is provided by biological destruction of organic matter [1–3].

The evolution of most bogs is a relatively long natural process which is an important constituent of the functioning of a unified natural ecosystem. On the other hand, water-logged areas are of rather widespread occurrence, which have resulted from human economic activity. The contemporary natural-anthropogenic bog systems are in isolation; their existence is, on the one hand, a naturally occurring process and, on the other, they are evolving as a result of a direct or indirect anthropogenic impact [1, 4–6]. Such formations are exemplified by the ecosystems along the eastern shores of Lake Baikal. Here, with a rise in the lake's overall water table caused by the hydraulic constructions on the Angara river, the bog formation processes have intensified [7, 8]. The implications of such processes involve the formation of bog waters of a special kind.

Bog complexes are of intrinsic scientific interest as a study area for investigating the natural-anthropogenic processes in the interactive mode where the anthropogenic component is regarded as natural conditions for the functioning of the overall ecosystem. As an example we refer to the extensive areas of the Arangatuiskii bog massif on the isthmus of Svyatoi Nos Peninsula where a rise in Lake Baikal's water table caused changes in the development of the ecosystem as a whole.

The present ecological status of biotopes in conditions of a phreatic rise is due primarily to changes in hydrological, hydrochemical, microbiological, biological and other characteristics, and the objective of this paper is to investigate these characteristics.

OBJECT AND METHODS

For the territory of the Arangatuiskii bog massif we compiled the landscape-typological map identifying the biogeocenoses with sampling sites (Fig. 1). Water samples for analysis were collected from wells of each bog phytocenosis. *Point 1* – littoral portion of Lake Mal. Arangatui, with the bottom covered by a layer of decayed plant remains. *Point 2* – bog biotope with sedge/horse-tail vegetation; the bottom sediments are comprised of weakly decomposed peat. Gases are liberated at these two points. *Point 3* – sedge-forb-hypnum moss bog located along the western boundary of the Arangatuiskii bog massif at a distance of 300–500 m from the shore of Barguzin Gulf. Samples were collected from a water-logged area where microbial fouling occur on plants in the water layer. *Points 4* and *5* are small bog areas, the surface of which is the home of the discharge of deep-seated thermal waters from the Kulinye Bolota mineral spring. *Point 6* – sample collected directly above the spring that immersed as a result of a rise in the water table of Lake Baikal. *Point 7* – water sample from Chivyrkuiskii Bay of Lake Baikal.

A hydrochemical analysis of water was carried out,

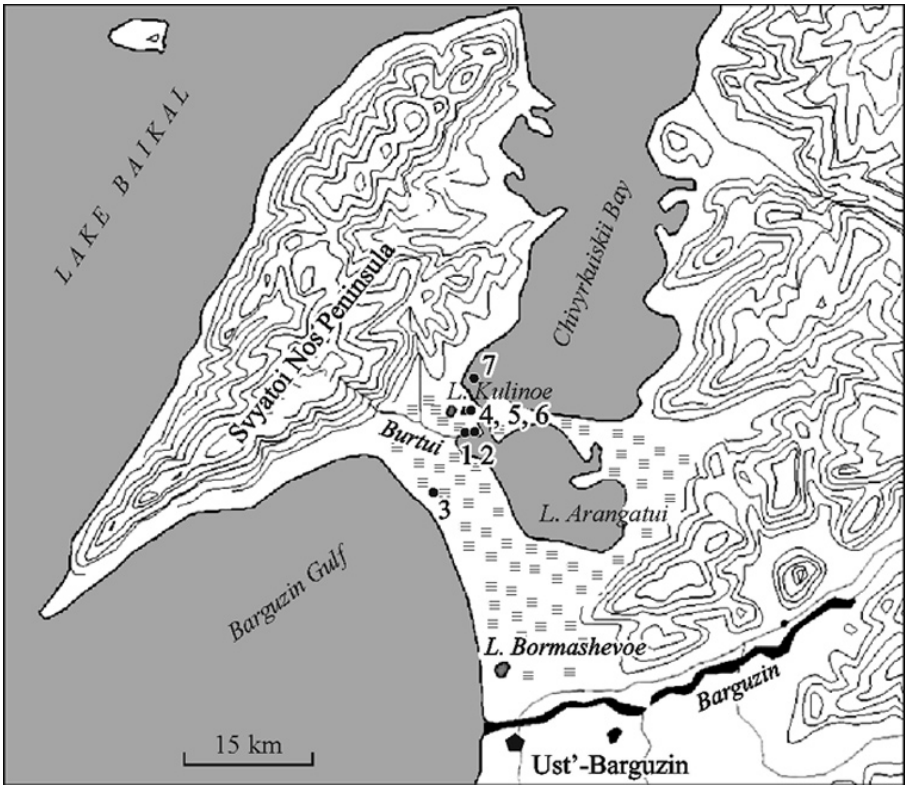

Fig. 1. Study area.
(*1*) –(7) sampling points.

following generally accepted techniques [9]. Water and bottom sediment samples were collected with Molchanov's bathometer, and with the stratometer. In freshly collected samples, we determined pH, CO_2 and O_2 concentrations, and biogenic elements. The numbers and activity of microorganisms were determined under laboratory conditions: cellulolitics and proteolitics – by the method of effective dilutions in Pfennig's liquid medium with substrates (filter paper and peptone), and amilolitics and sulfate-reducing bacteria – on Pfennig's dense medium with substrate (starch), and on Widdel's medium [10]. The composition of gases was studied with gas-liquid chromatograph M 3700 (detector – catarometer, carrier gas – argon). CO_2 was determined with column Sovpol B (3 m in length, and 3 mm in diameter), and methane, hydrogen and oxygen – with column Molseive 5A (3 m in length, and 2 mm in diameter); the chromatography conditions: 30ºC×70ºC×90ºC.

The rate of microbiological processes was determined by radio isotope methods in different modifications [11–12]. Upon introducing the radioactive label into the sample, the samples were incubated *in situ* for 12–24 hr. As labels, we used uniformly labeled solutions: for determining the intensity of dark fixation of CO_2 and autotrophic methanogenesis – $NaH^{14}CO_3$, for sulfate reduction – $Na_2{}^{35}SO_4$, and for methane oxidation – $^{14}CH_4$. Upon completion of incubation, the samples were fixed with 0.2–0.4 mL of 40% formalin, and 1 mL of 20% zinc acetate was additionally introduced into samples containing $^{35}S^{2-}$. A subsequent processing was carried out according to methods reported in [11, 13]. Radioactivity of the fixed samples was determined with liquid scintillation counter RackBeta (LKB, Sweden).

DISCUSSION

A small depth of the aeration zone, and a relatively high water permeability of the peats of the Arangatuiskie lake-bog formations are favorable for an intimate moisture exchange between groundwater/bog waters, the aeration zone and the atmosphere. In the aeration zone there occurs vadose water produced by the thawing of ice inclusions in peats. The characteristic properties of the winter-spring season are, to a significant extent, determined by the character of snow cover distribution and disappearance. Seepage of snowmelt waters through the frozen peat layer causes an abrupt rise of groundwater/bog waters with the mean rate of 2 cm per day, reaching a level 0.2–0.4 m above the day surface.

After the disappearance of snow, groundwater/bog waters are involved in the formation of the water balance. As a result of depletion of snowmelt waters and maximum possible evaporation, their level decreases to a summertime minimum. A rise is concurrent with summertime rainfall; however, a marked effect is produced only when the value of its ten-day amount exceeds 20 mm. During the period of rainfall, the groundwater/bog water table rises to the day surface, so that most of the bogs turn into quagmires. At the onset of peat freezing and cessation of rainfall in the first ten-day period of October, the groundwater/bog water table decreases to a winter-equilibrium minimum. The hydrogeological conditions are discussed at greater length in [14].

The rise of the water level in Lake Baikal involved a disturbance to the regime of subterranean waters and the pre-existing water balance, and a redistribution of overland and subterranean runoffs, which affected the natural landscapes and the state of soil cover. According to the topographic maps from the year 1954, the Burtui river emptied into Lake Baikal in the area of Barguzin Gulf. Later, within the confines of the isthmus of Svyatoi Nos Peninsula, the river changed the direction of its course. At present the river flows into Lake Arangatui where almost impassable quagmires came into existence.

A deceleration of the runoff causes changes in the chemical composition of bog waters. The mineral bed of the bogs consists of carbonate loams, which affects the hydrochemical regime and gives rise to bog waters enriched with mineral matter. The reserves of biogenic substances are created mainly biologically; the main source for them is provided by mineral rock experiencing swamping.

Groundwater shows mostly a hydrocarbonate, calcium, calcium-manganese and sodium makeup, and less commonly a hydrocarbonate-sulfate makeup, with a mixed cationic composition; usually, mineralization does not exceed 0.6 g/dm^3. In a summer season, mineralization of bog waters and groundwater is increased due to evaporative concentration and capillary attraction of moisture from deep-seated horizons. Areas with shallow occurrence of subterranean waters develop salinization processes, the chemistry of which is varied: sulfate- and chloride-hydrocarbonate, sulfate-soda, and soda-chloride. The behavior of the processes of salinization and formation of such a variety of salts within a relatively small territory demands further detailed investigation.

Small streams that form within the bog show elevated concentrations of Ca^{2+}, HCO_3^-, SO_4^{2-}, NH_4^+, and NO_2^-, a high mineralization, and significant contents of organic matter. The highest contents of almost all microcomponents are observed along the margin of the bog in the elevated part and in waterlogged forests. In quagmires and tributaries, relatively large concentrations of trace elements undergo sorption on fine dispersed particles of metal oxides and humic acids; smaller amounts of trace elements are removed from solution and concentrate in the upper parts of the bogs on peats [14].

Bog waters are neutral waters. Near a mineral source, the pH values increase. In a summer season, surface water temperature in the bogs differs only slightly from air temperature. The water temperature in the bog waters at the time of our investigation was 32–34 ºC; in the gryphon of a mineral spring, it reached 62–65 ºC. Compared to the waters of Chivyrkuiskii Bay, the bog waters are enriched with organic matter, which is confirmed by high values of COD and humic acids, as well as by the occurrence of nitrites and by elevated contents of Fe_{tot}. The largest BOD values were observed in samples collected at point 6, suggesting a high activity of microbial communities (with the numbers of aerobic saprophytes reaching 10^8 cells/mL) (Table 1).

Gases released from bogs are nitrogen-methane (points 2 and 4) and methane-nitrogen gases in their composition. (points 1, 3, and 5). The nitrogen content reaches 86%; a relatively high content of methane, up to 76%, was revealed. The content of carbon dioxide in samples reaches 5%. The absence of CO_2 in gas samples collected at points 4 and 5 is attributed to its fixation by alkaline waters of the spring, and to its passage into the forms of carbonic acid (Table 2).

Bogs are the home to intense activity of microorganisms, which is facilitated by the presence of favorable hydrochemical parameters of water, and by rich contents of autochthonous and allochthonous organic and mineral matter. Microorganisms are involved in organic matter production and destruction, the production of biogenic gases, and in the formation of aero- and anaerobiosis in waters and bottom sediments of bogs. Among the indicators of activity of the microbial community is dark assimilation of CO_2 [13] – a process resulting in the production of organic matter. Assimilation can occur in the light (in the process of photosynthesis) as well as in darkness (dark assimilation or dark fixation of CO_2). The rate of dark assimilation is an integral indicator of activity of the entire microbial community in the ecosystem. The intensity of dark fixation of carbon dioxide in the biotopes under study is 0.20–2.88 mg of C/dm^3 per day (Fig. 2, a). The highest activity of the microbial community is observed in biotopes located in the vicinity of a thermal spring.

In the case of intense activity of aerobic microorganisms, the water and bottom sediments develop reductive conditions. In a peat deposit with peat not exceeding 0.7 m in thickness, the 0.3-m layer sustains oxidizing conditions (500–900 mV), with a decrease in Eh from –140 to –180 mV observed down the profile. When the values of Eh are low, anaerobic microorganisms show active behavior. In the terminal stages, sulfate-reducing and methane-forming bacteria are involved in organic matter destruction. The rate of sulfate reduction in the bog biotopes under study varied from 6.35 to 16.02 mg S/(dm^3·day) (see Fig. 2, b). Another terminal stage of organic matter destruction is the methanogenesis. These two processes are thought of as being competitive with each other. The autotrophic and acetoclastic methanogenesis was determined (see

Table 1. Hydrochemical composition of bog ecosystems on the Svyatoi Nos isthmus of Lake Baikal

Parameters	Sampling points						
	1	2	3	4	5	6	7
T, ºC	22	22	19	34	32	65	14
pH	7.08	6.70	6.70	9.36	8.96	9.50	7.95
BOD, mg/dm^3	0.63	1.71	0.08	2.96	3.33	4.08	–
O_2, mg/dm^3	4.3	3.5	2.0	0.3	0.4	5.1	–
CO_{2free}, mg/dm^3	n/d	n/d	4.4	n/d	n/d	26.4	–
Mineralization, mg/dm^3*	190	210	225	–	–	290	145
HCO_3^-, mg/dm^3	79.3	134.2	152.5	123.0	195.2	366.0	86.4
CO_3^{2-}, mg/dm^3	n/d	18	30	78	60	108	–
SO_4^{2-}, mg/dm^3*	10.75	12.9	9.05	–	12.0	16.0	9.6
Cl^-, mg/dm^3	1.9	3.0	3.0	30.2	35.6	32.6	0.8
NO_3^-, mg/dm^3	0.17	0.26	0.50	1.20	1.22	0.26	0.70
NO_2^-, mg/dm^3	0.079	0.024	0.014	0.044	n/d	0.003	–
PO_4^{3-}, mg/dm^3	0.076	0.107	n/d	0.034	0.037	0.006	–
Ca^{2+}, mg/dm^3	11.3	10.8	17.8	3.8	4.1	48.1	16.1
Mg^{2+}, mg/dm^3	2.6	3.9	2.8	6.0	6.0	10.7	3.2
Na^++K^+, mg/dm^3*	10.6	12.5	15.7	–	18.2	22.7	9.8
NH_4^+, mg/dm^3	n/d	0.008	0.460	0.066	0.130	0.280	–
Fe_{tot}, mg/dm^3	0.63	0.73	1.80	1.15	0.95	0.28	0.18

Note. n/d – not detected, “–” – not determined, *samples were collected in the wintertime.

Table 2. Qualitative and quantitative composition of marsh-gases (%)

Sampling points	H_2	CO_2	O_2	N_2	CH_4
1	0	2	2	18	76
2	0	4	1	55	40
3	0	5	0	42	53
4	0.3	0	2	86	12
5	0	0	4	44	52

Fig. 2, c, d) – methane formation was largely autotrophic in all the bog biotopes used in the study.

The rate of autotrophic methane production in bottom sediments and microbial mats varied from 1.9 to 284.3 μL CH_4/(dm^3·day). The highest rate of methane production was revealed in the microbial mat of point 3. In bottom sediments of points 4 and 5, the methanogenesis was proceeding at a lowest rate – 2.7 and 1.9 μL CH_4/(dm^3·day), respectively. Methane is produced from acetate in bog ecosystems at a lower rate – from 0.25 to 2.15 μL CH_4/(dm^3·day). The highest rate of acetoclastic methanogenesis was revealed at point 3. In microbial mats, the activity of the methanogenic community is higher than that in the bottom sediments of these same biotopes.

Minus values of Eh in bogs occur in deeper soil layers where anaerobic processes can have a much higher intensity. The evidence for this is provided by the fact that the composition of liberated marsh-gas shows a high percentage of methane (see Table 2). Methane produced under reductive conditions undergoes oxidation by a highly specialized group of bacteria, methanotrophs, in aerobic settings. The activity of these bacteria in the bog ecosystems under study varied from 33.9 to 181.6 μL CH_4/(dm^3·day). The highest intensity of methane oxidation was observed in bottom sediments of a mineral spring.

The values of intensities, and the balance equations of microbial processes can be employed to calculate the number of organic carbon used by bacteria in the production of methane and hydrogen sulfide [13]. Sulfate reduction consumes 5.5 to 12.7 μg C/(dm^3·day). The process of autrophic and acetoclastic methanogenesis consumes 7.6 to 657.0 and 0.04 to 0.48 μg C/(dm^3·day), respectively. The microbial community uses 7.6 to 657.0 μg C/(dm^3·day) for methane production, whereas sulfate reduction consumes 6.5 to 12.3 μg C/(dm^3·day). Furthermore, most of methane is produced by autotrophic methanogenes which use in the synthesis hydrogen and carbon dioxide – products of organic matter destruction. Acetate-using methanogenes consume in the synthesis of methane up to 0.50 μg C/(dm^3·day). Upon determining the activity

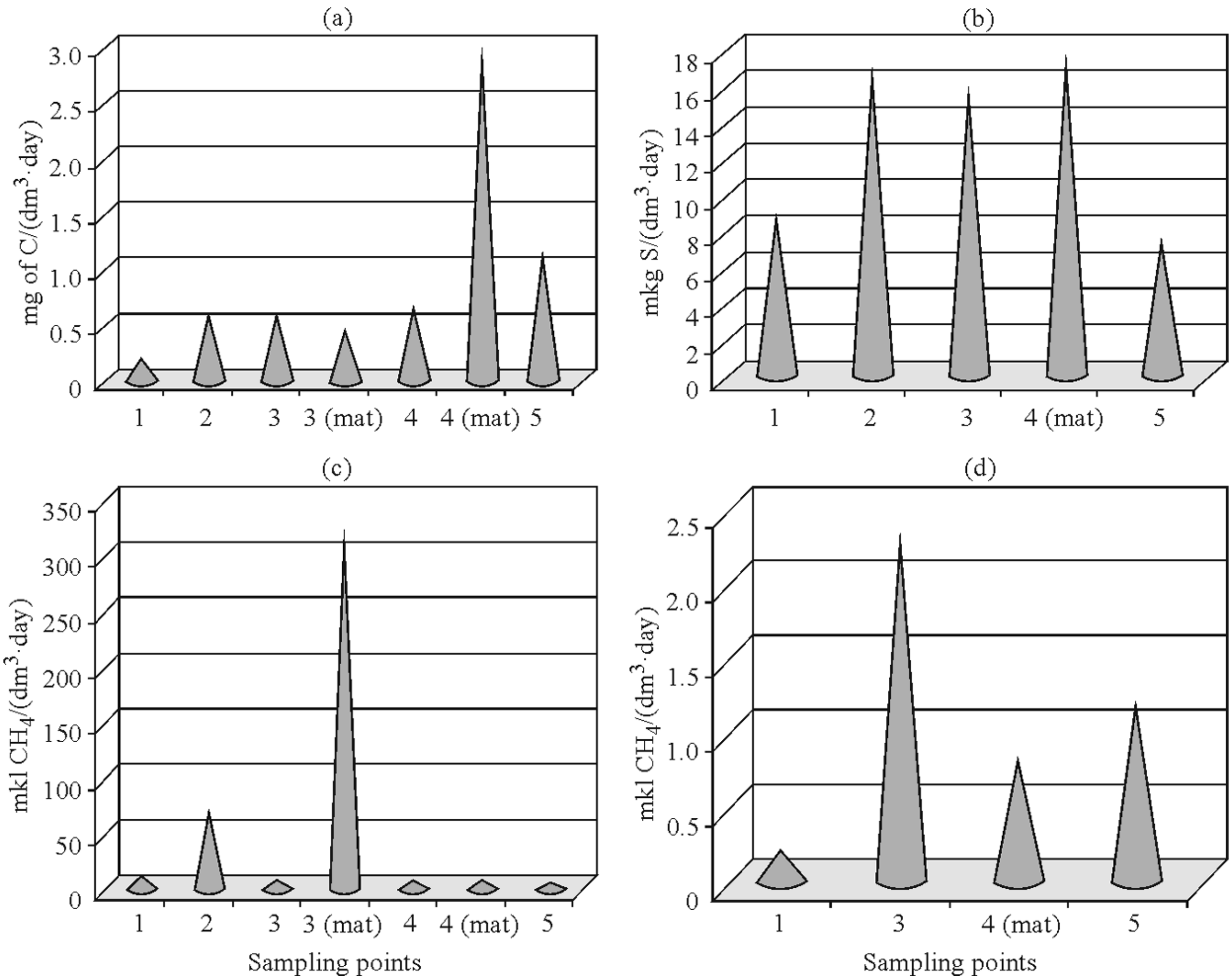

Fig. 2. The rate of microbiological processes in bottom sediments and microbial mats of bog biotopes.
(a) dark fixation of CO_2, (b) sulfate reduction, (c) autotrophic methanogenesis, (d) acetoclastic methanogenesis.

of sulfate reducers, it was shown that they synthesize up to 17.5 μg $H_2S/(dm^3{\cdot}day)$. In bog biotopes with neutral pH values and with fresh water, a dominant terminal process is represented by methanogenesis, whereas in alkaline biotopes wit mineralized water the sulfidogenesis is comparable to methane formation. Also, the bog ecosystem creates anaerobic conditions which are favorable for burial of organic matter in bottom sediments.

The labeled methane-based radioisotope technique was used to determine the distribution of carbon in methane. In the process of methane oxidation, from 8 to 22% of carbon is incorporated in the biomass of cells and in organic exometabolites, with 88 to 92% of labeled methane passes into CO_2. Methane undergoes the highest oxidation in biotopes at a mineral spring.

A quantitative assessment of the activity of microorganisms shows that aerobic and anaerobic bacteria take an active part in the cycle of matter and energy in the bog ecosystem of the isthmus of Svyatoi Nos Peninsula. Microorganisms are involved in the processes of organic matter production and destruction, formation and intake of gases, and transformation of biogenic and abiogenic substances which are supplied in transit from bogs to Lake Baikal.

CONCLUSIONS

As a result of a rise in the water table of Lake Baikal, the bog formations of the Svyatoi Nos isthmus are evolving under new conditions, with an increase in water-logged areas and with an accelerated development of bogs without a pronounced anthropogenic factor in the overall natural development. There are taking place concurrent changes in development directedness of the isthmus' ecosystem as a whole which are associated primarily with hydrological, hydrochemical and characteristics of bogs. The hydrochemical composition of the bog biotopes has transformed, and there has occurred a particularly clearly pronounced intensification of the microbiological processes influencing the formation processes of chemical composition of waters.

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