BIOGEOCHEMISTRY

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*ASPECTS OF ORGANIC SUBSTANCE AND NUTRIENT DISTRIBUTION IN SMALL LAKES AND LIMITATION OF THEIR TROPHICITY IN THE EUROPEAN TERRITORY OF RUSSIA AND IN WEST SIBERIA**

SUMMARY. The distribution of lakes according to their trophic state is characterized, the organic substance and nutrient ratio in the latitudinal aspect are represented, as a result of the large-scale research of the water chemistry in the small lakes in the European territory of Russia (ETR) and West Siberia (WS). The distinctive feature of the WS lakes in the tundra, forest-tundra and taiga zones is high nitrate concentration in the water and higher trophic level, in comparison with the lakes of the same ETR zones. The zonal regularities of the lake trophic limitations for main nutrients are distinguished. It is shown that in the lakes of the ETR tundra and taiga zones, the conditions for algae development are limited for both phosphorus and nitrogen, although at the critical level, they are more limited for nitrogen. In the lakes of the WS tundra and taiga zones, the conditions for algae development are not limited at the critical level for both phosphorus and nitrogen. The shortage of mineral phosphorus occurs at the lower trophic levels, whereas the shortage of nitrogen occurs at the higher trophic levels.

KEY WORDS. Nutrients, autochthonous and allochthonous organic substance, trophic status, limitation, eutrophication.

Under the influence of anthropogenic activity, the natural biogeochemical cycles of elements have undergone significant changes. According to [1], since 1700, the global changes of the C, N, and P amounts included in the turnover, have lead to the significant increase in their flow into water bodies, due to the land-use changes, fertilizer application, and wastewater inflow. With anthropogenic eutrophication and non-toxic water pollution by organic substance, the same processes occur as in the evolutionary lake development, due to the internal factors, but at higher rates [2].

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Yu. Odum mentions that «the value of concept of the limiting factors which are "functionally important" for an organism, is in the fact, that it provides a starting point for ecological research. At a steady state, the limiting factor will be that vital substance, the available quantity of which is the closest to the necessary minimum — "the minimum law" by Liebig» [3].

The purpose of this paper is to characterize the present distribution of small lakes according to their trophic status and the contents of nutrients and organic substance in the latitudinal aspect, to reveal the regularities of the limitations of lake productivity in the latitudinal aspect.

The data and methods of the research. The work is based on the results of the original research of the chemical waters composition of about 300 small lakes in the European territory of Russia (ETR), along a transect from the North to the South. The research was carried out in 1999-2003 [4], and continued in 2008, and supplemented by the research of 137 lakes in the territory of West Siberia (WS), carried out in 2011 according to the same methodology. The study included the lakes which were not subject to any direct sources of pollution, and having the water surface area not more than 20 km^2. To minimize the influence of interannual and seasonal variations, the samples were taken in a short period of late-autumn cooling, when homothermy usually occurs and there is no stratification, when there are no significant fluctuations of vegetation processes, but their "smoothed" level is represented. This principle of research allows comparing the considered lakes located in different natural and climatic zones.

The chemical composition of the waters was determined with the uniform technique; the correctness of the results obtained was confirmed during the international intercalibration. The analytical work program included determining pH, electrical conductivity (χ), the main mineralization ions, colour (Col), permanganate oxidability, nutrients and their forms, and microelements.

Organic nitrogen (N_{org}) is calculated as the difference of the total N and the sum of ammonium and nitrate N. Total organic carbon (TOC) is calculated on permanganate oxidability (PO) [5]: TOC=0.764*PO+1.55 n=178, r=0.79.

Results and discussion. One of the important sources of nutrients is precipitation, therefore, even the lakes which do not receive direct runoff, are subject to environment changes. The zone feature is the inflow of the elements with precipitation which decreases towards the South. The soil is an important link on the way of nutrients (N) migration, and its regulatory function depends on the intensity of biological processes, the composition and the absorption capacity of soil, temperature and moistening conditions of the territory. The zone feature (decrease to the South) is reflected in the increase of intensity of the consumption and return processes of inorganic compounds to the South, where the natural biological cycles of nutrients are changed into agrogeochemical ones. The contents of the organic substance (OS) and the nutrients (N) in lakes, as well as the colour and electrical conductivity of water in various natural zones are presented in Table 1. Natural zoning predetermined the increase in the productivity of terrestrial and water ecosystems, and in the OS and N contents, which is observed in the lakes of ETR: both the total phosphorus and nitrogen, and their mineral forms increase.

Table 1

Colour, organic substance, and nutrients in the lakes of various natural zones (the numerator is the median; the denominator is the content limits)

Natural zones	n	pH	χ, μS/cm	Col., degree	TOC, mgS/l	P_{tot}, μg/l	PO_4, μg/l	N_{tot}, μg/l	NH_4, μg/l	NO_3, μg/l	Si, mg/l
European territory of Russia											
Tundra	14	6.57 / 6.15-6.86	34 / 26-55	15 / 7-31	3.9 / 3.1-6.0	4 / 1-9	0	107 / 48-310	8 / 1-20	2 / 1-15	1.00 / 0.17-2.13
Forest-tundra	21	6.43 / 4.65-6.86	25 / 16-54	36 / 4-266	6.0 / 2.8-18.4	6 / 2-46	0 / 0-7	180 / 72-386	8 / 1-27	2 / 1-7	1.45 / 0.10-3.95
Northern taiga	72	6.89 / 4.15-7.51	29 / 8-97	33 / 0-320	6.8 / 1.6-24.3	5 / 1-54	0 / 0-34	187 / 57-477	10 / 1-85	3 / 0-480	2.70 / 0.03-7.07
Middle taiga	84	6.73 / 5.72-7.60	32 / 13-117	52 / 4-202	8.8 / 3.3-24.9	17 / 4-142	1 / 0-35	332 / 108-1,290	23 / 1-690	3 / 1-70	1.37 / 0.06-13.1
Southern taiga and mixed forests	49	7.44 / 4.72-8.45	126 / 14-330	48 / 8-156	10.0 / 4.8-32.2	25 / 8-179	4 / 1-35	800 / 295-3,940	174 / 1-740	25 / 1-289	0.90 / 0.05-5.84
Forest-steppe and steppe	18	7.96 / 6.78-9.55	436 / 86-1072	24 / 10-120	7.8 / 4.1-57.7	33 / 12-257	9 / 1-256	1,045 / 480-2,910	580 / 180-1,610	120 / 20-220	0.52 / 0.06-9.15
West Siberia											
Tundra	42	6.44 / 5.30-7.71	37 / 15-584	16 / 1-355	6.1 / 1.3-10.8	90 / 4-189	14 / <3-35	905 / 110-2,340	38 / 8-322	534 / 1-2022	0.55 / 0.04-1.36
Forest-tundra	10	5.09 / 4.81-5.96	24 / 17-34	63 / 57-160	12.1 / 8.2-11.6	49 / 38-79	<3	830 / 350-1,240	61 / 8-865	154 / 16-431	0.12 / 0.11-1.79
Northern taiga	22	5.56 / 4.94-6.90	25 / 15-65	38 / 5-180	7.3 / 2.2-24.1	40 / 9-175	≤3 / <3-34	960 / 190-1,650	110 / 9-1,188	213 / 10-530	0.08 / 0.01-0.81
Middle taiga	36	5.70 / 4.54-7.42	43 / 18-386	80 / 7-146	11.4 / 1.5-20.3	25 / 3-158	≤3 / <-50	815 / 20-2270	203 / 8-954	80 / 4-1,546	0.14 / 0.01-2.48
Southern taiga	16	7.39 / 6.50-7.68	333 / 49-565	54 / 14-166	13.7 / 7.0-20.7	54 / 21-146	31 / 21-98	1,445 / 400-5,090	20 / 8-567	553 / 4-3,873	4.67 / 0.09-6.44
Forest-steppe and steppe	11	7.92 / 7.47-8.75	1252 / 683-2,859	34 / 21-89	26.5 / 19.0-39.4	20 / 10-48	9 / 3-18	2,580 / 1,680-3,280	22 / 0-1,040	72 / 28-1,011	2.59 / 0.25-8.45

However, the distinctive feature of the WS lakes is the high nitrate nitrogen content in tundra, forest-tundra, northern and middle taiga, which may be explained by the additional nitrogen input in the water producing areas and in lakes (be it the nitrogen oxide fallout or other ways, see the papers by T.I. Moiseyenko, L.P. Panicheva et al. in this issue), due to the exploration of WS oil and gas resources, that makes fundamental changes in the trophy of lakes in this territory. The higher phosphate levels in the WS lakes than those in the ETR lakes should also be noted.

For analyzing the trophic status of lakes, the natural zones with the lakes under investigation were grouped, according to their climatic conditions, into the following areas: tundra (tundra and forest-tundra), taiga (northern and middle taiga), forests (southern taiga and mixed forests), steppes (forest-steppes and steppes).

The trophic status is evaluated on the total phosphorus (TP) content during the autumn period, on the basis of the following classification: TP<10 μg/l — oligotrophic, TP 10-35 μg/l — mesotrophic, TP 35-100 μg/l — eutrophic, and TP>100 μg/l — hypertrophic. This classification proposed in [6] conforms with the classification in [7], in which to evaluate the trophic status the following factors are selected: the total phosphorus and *a*-chlorophyll contents, and the transparency. In addition, ultraoligotrophic lakes (TP<4 μg/l) are distinguished. The distribution of lakes according to their trophic status is presented in Table 2. In the tundra and taiga of ETR, the dominating type of lakes is oligotrophic; in forests, the dominating type is mesotrophic; and in steppes, it is eutrophic and hypereutrophic, whereas in the tundra, taiga and forests of WS the dominating type of lakes is eutrophic, and in the forest-steppes it is mesotrophic. The reduced productivity of the lakes in WS forest-steppes can be explained by their salinity, it inhibits the algae growth, if we take into account the high values of the electrical conductivity of water as a mineralization feature (see Table 1), this growth can be also explained by the more sharply continental climate than in ETR.

For example, in the analysis of more than 1,000 lakes of Europe presented in [8], it was found out that the values of TP, TN, and *a*-chlorophyll increase at the alkalinity < 1000 μg-eq/l, whereas at the alkalinity >1000 μg-eq/l these values, on the contrary, decrease.

When the organic carbon / organic nitrogen ratio is equal to 12, the organic substance (OS) of the autochthonous origin dominates; if the ratio is equal to 47, the OS of the allochthonous origin dominates [9]. In tundra and taiga, the growth of colouring in lakes (see Table 1) is caused by removing the OS of the allochthonous origin, and the acidic reaction of the high-coloured waters is formed by the inflow of marsh waters. In the forests and steppes, the colouring indicates rather the strengthening of soil humification, than the bogginess of the water producing area; more nutrients comes to lakes, which increases the productivity of water bodies and decreases an allochthonous OS component (TOC/N_{org}). As it can be seen in Table 2, when the trophic level increases, the TOC/N_{org} value decreases; this also indicates the increase in the proportion of the autochthonous OS. In this case, we can observe the increase of OS enriched not only with nitrogen, but also with phosphorus, judging by the TOC/TP index.

Table 2

Distribution of lakes according to various degrees of trophic status and TOC/Norg and TOC/TP factors (the median; in brackets 1 quartile (25%) and 3 (75%) quartiles are given)

Natural zone		Number of lakes		Number of lakes, %		TOC/N_{org}		TOC/TP	
		ETR	WS	ETR	WS	ETR	WS	ETR	WS
tundra	ultraoligotrophic	6	0	19	0	53 (47-58)		1,181 (1,058-1,284)	
	oligotrophic	16	4	52	8	41 (34-45)	51 (16-127)	848 (668-1,043)	712 (365-1,117)
	mesotrophic	9	15	29	29	27 (24-29)	42 (24-142)	477 (431-577)	206 (141-307)
	eutrophic	0	31	0	59		37 (20-69)		125 (75-201)
	hypertrophic	0	2	0	4		25 (24-27)		52 (49-54)
taiga	ultraoligotrophic	16	2	10	3	43 (29-49)	33 (31-35)	1,633 (1,175-1,789)	1,641 (1,589-1,692)
	oligotrophic	64	7	38	12	41 (33-47)	59 (49-343)	1,264 (1,016-1,572)	1,037 (567-1,614)
	mesotrophic	60	21	36	36	26 (24-33)	40 (27-51)	470 (360-607)	537 (271-743)
	eutrophic	22	24	13	42	24 (21-27)	30 (21-50)	220 (165-291)	212 (119-326)
	hypertrophic	4	4	2	7	8 (7-9)	29 (18-41)	90 (47-128)	96 (71-119)
forests	oligotrophic	3	0	6	0	19 (18-21)		739 (644-810)	
	mesotrophic	31	3	61	19	21 (16-27)	13 (13-15)	469 (355-611)	669 (639-809)
	eutrophic	15	11	29	69	16 (13-21)	16 (14-28)	204 (159-235)	250 (168-345)
	hypertrophic	2	2	4	12	13 (11-15)	56 (41-71)	163 (145-181)	123 (121-125)
steppes	oligotrophic	0	1	0	9		17		2,654
	mesotrophic	13	7	44	64	21 (11-41)	14 (12-19)	371 (307-474)	1,186 (1,126-1,278)
	eutrophic	10	3	33	27	7 (5-11)	13 (12-13)	142 (87-413)	737 (684-826)
	hypertrophic	7	0	23	0	5 (3-23)		53 (28-130)	

Unfortunately, the phytoplankton demand for various nutrition elements has been studied insufficiently. The maximum interest in this problem was demonstrated in 1940s-1980s, and the fullest review of these works is presented in [10]. Though the demand of different types of algae for certain nutrition elements varies, the excess of an element in water can sometimes inhibit their development, and most algae are able to store elements in much greater amount than it is needed for their normal growth. Yet the limit concentrations of elements in water (as a territorial feature) can be a good indicator of water environment conditions for the algae development, when a great number of water bodies are compared. Phosphorus, inorganic nitrogen, and silicon are considered limiting, when their concentration is lower than 10 μg/l, 300 μg/l, and 0.5 μg/l, respectively [11]. These concentrations can be considered as the lower limits for the optimal algae development. However, the limit, at which their development stops or their amount is reduced to an insignificant minimum, is also important. According to U. Müller (cited in [12]), at the Si content lower than 0.5 mg/l, *Asterionella formosa* became extinct, and if it was lower than 0.1 mg/l, the diatoms did not develop. The issue of P and N limit concentrations is more contentious. I.A. Kiselev (cited in [10]) came to the conclusion, that the limiting phosphorus doses for some diatoms, below which the reproduction stops, are equal to 0.05-0.06 mcg / 106 cells. Conventionally the lower limit (the minimum concentration) of the termination of algae development will be 1 mcg/l for phosphates and 7 μg/l for nitrates, the latter is set according to the N and P ratio in algae cells.

In the ETR tundra, the nutrient concentrations in lakes do not reach the optimum conditions for phosphorus and nitrogen, being more limited at the critical level on nitrogen, than on phosphorus (Table 3). Almost the same situation remains in taiga, but to a less extent — 25% of lakes are limited on P at the critical level. However, the lack of productivity limitation for the WS tundra and taiga lakes at the critical level, both on nitrogen and on phosphorus, is regionally determined, but about 80% of lakes do not reach the optimum concentrations in phosphorus for the algae development, and about 40% of lakes do not reach the optimum concentrations in nitrogen. In the ETR forests, there are 39% of lakes, where the phytoplankton development is limited on nitrogen at the critical level, but there is no limitation on phosphorus; however, about 60% of lakes do not reach the optimum level of nutrient concentration on nitrogen, and practically all of them do not reach the optimum level on phosphorus, whereas all the WS lakes are in the optimum conditions. In the ETR and WS steppes, there is no productivity limitation at the critical level, and the lakes are in better conditions on nitrogen, than on phosphorus. Note that the more is the number of lakes with productivity limited on N and P, the lower is their trophic level, that partly explains the oligotrophic nature of the lakes. The limitation of the algae development on Si occurs at higher trophic levels, that shows its utilizing by the diatoms in the ecosystem with the productivity intensification. Moreover, due to the dominance of higher trophic levels in the lake distribution in the WS tundra and taiga, the Si exhaustion is the largest, and in these conditions (when there is no limitation on phosphorus and nitrogen) it becomes a limiting element.

In the biological research practice, the index of the relationship between nitrates and phosphates (NO_3/PO_4^{3-}) characterizes the change conditions for dominant species and is the basis of the "resource" theory [13]. The experimental study [14] shows, that significant changes of growth rates of blue-green algae at different values are not observed. They are able to increase the biomass using smaller amounts of N per biomass unit, but as for the consumption of nitrates and phosphates and the exponential growth speed, they overtake the diatom values. Besides, the maximum relative growth for the latter was registered at the optimum NO_3/PO_4^{3-} ratio; although, at low phosphate concentrations in water, they can be competitors for it. Thus, by the end of the vegetative period, the P deficiency or exhaustion is higher at low trophic levels, and decreases with the trophic status growth, especially in steppes as a more productive zone (Table 3), where blue-green algae often dominate.

At TN/TP<10 ratio, the algae development is considered to limit the nitrogen, at >17, it is considered to limit phosphorus, the optimal conditions are at 10-17 [15]. According to the gradations of this relationship, in the studied lakes of all zones, nitrogen limits the productivity (Table 3). The most justified value for the lake recovery tasks becomes TN/TP, when its change is considered in a long-term series of observations in comparison with the change of P and N loading levels on a water body, that was demonstrated in [16-17]. As we can see from Table 3, the higher is the trophic level, the higher is P accumulation in relation to N in lake ecosystems. Therefore, the trophic degree (the phosphorus accumulation level) characterizes the ratio of organic carbon to the total phosphorus (TOC/TP) more informatively, than the ratio of the total nitrogen to the total phosphorus (TN/TP). In ultraoligotrophic lakes TOC/TP>1,000, in oligotrophic lakes it is TOC/TP >600, in mesotrophic lakes it is 300-600, in eutrophic lakes it is 150-300, and in hypertrophic lakes TOC/TP <150 (Table 2). Besides, the ratio of allochthonous and autochthonous OS, characterized by TOC/N_{org} (Table 2), can strongly influence the TN/TP value. Though at different trophic levels it can vary, but the allochthonous OS dominates in oligotrophic lakes, whereas the autochthonous OS, enriched with nitrogen, dominates in eutrophic and hypertrophic lakes.

Conclusion. The limit concentrations of elements, as the indicators of the hydrobiont development limitation, can be good territorial characteristics, and they reflect the zone and regional specific features. It is shown, that in the lakes of the ETR tundra and taiga, the conditions for the algae development are characterized by the limitation both for phosphorus and for nitrogen, but at the critical level it is more for nitrogen, whereas, due to regional specific features, in the WS lakes there is no limitation at the critical level both for nitrogen and for phosphorus. In the forests and steppes, the productivity limitation occurs at the lowest level of optimal conditions for the algae development, and the limitation is more for phosphorus, than for nitrogen. At the low trophic levels, the deficiency of mineral phosphorus is more apparent, whereas at the high levels, it is more apparent for nitrogen. The level of biological activity is characterized mainly by the origin parameters of organic substances (TOC/N_{org}), and the degree of trophic status is characterized rather by the relation of organic carbon to the total phosphorus (TOC/TP), than the ratio of the total nitrogen to the total phosphorus (TN/TP).

Table 3

Percentage lake distribution at various limitation degrees (1 is the lower limit of the optimal development, 2 is the concentration at which the development stops) on phosphorus, nitrogen, and silicon, as well as on the ratio of nitrogen to phosphorus, at different trophic levels in various climatic zones (the numerator is for the lakes of the European territory of Russia, the denominator is for the lakes of West Siberia)

Natural zones		PO_4^{3-}		N		Si		NO_3^-/PO_4^{3-}		TN/TP		
		<10 µg /l	<1 µg /l	<300 µg /l (total amount of NH_4^+ and NO_3^-)	<7 µg /l (NO_3^-)	<0.5 mg/l	<0.1 mg/l	<7	>7	<10	10-17	>17
		1	2	1	2	1	2					
tundra	Total for the zone	100 / 81	58 / 0	100 / 44	81 / 2	26 / 60	3 / 21	42 / 8	58 / 94	0 / 33	6 / 25	94 / 42
	ultraoligotrophic	100 / –	83 / –	100 / –	67 / –	17 / –	0 / –	17 / –	83 / –	0 / –	0 / –	100 / –
	oligotrophic	100 /100	44 / 0	100 / 75	94 / 25	13 / 75	0 / 50	56 / 25	44 / 75	0 / 0	6 / 25	94 / 75
	mesotrophic	100 / 87	67 / 0	100 / 47	67 / 0	56 / 100	11 / 40	33 / 0	67 / 100	0 / 20	11 / 7	89 / 73
	eutrophic	– / 77	– / 0	– / 42	– / 0	– / 74	– / 10	– / 10	– / 90	– / 42	– / 32	– / 26
taiga	Total for the zone	92 / 78	25 / 0	96 / 38	83 / 2	17 / 74	7 / 43	67 / 21	34 / 79	3 / 22	25 / 7	72 / 71
	ultraoligotrophic	100 / 100	50 / 0	94 / 100	69 / 0	19 / 100	19 / 50	38 / 50	62 / 50	0 / 0	0 / 0	100 / 100
	oligotrophic	100 / 71	28 / 0	100 / 57	94 / 14	8 / 86	5 / 43	64 / 57	36 / 43	0 / 14	2 / 0	98 / 86
	mesotrophic	93 / 90	25 / 0	100 / 24	88 / 0	23 / 81	7 / 38	70 / 10	30 / 90	2 / 0	38 / 5	60 / 95
	eutrophic	68 / 79	0 / 0	91 / 42	64 / 0	27 / 61	5 / 50	86 / 13	14 / 87	14 / 38	72 / 8	14 / 54
	hypertrophic	25 / 0	0 / 0	25 / 25	75 / 0	25 / 50	25 / 25	100 / 50	0 / 50	25 / 75	50 / 25	25 / 0
forests	Total for the zone	94 / 0	0 / 0	63 / 0	39 / 6	35 / 13	6 / 6	61 / 19	39 / 81	6 / 13	20	74
	oligotrophic	100 / –	0 / –	100 / –	100 / –	33 / –	0 / –	100 / –	0 / –	0 / –	0 / –	100 / –
	mesotrophic	100 / 0	0 / 0	58 / 0	35 / 0	45 / 0	10 / 0	48 / 0	52 / 100	0 / 0	16 / 0	84 / 100

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