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EXPERIMENTAL ARTICLES

Effect of Suspended Mineral Matter on Production Characteristics of Bacterio- and Phytoplankton

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Abstract—The effect was determined of organo-mineral detritus (OMD), one of the components of suspended mineral matter in aquatic ecosystems, on the production characteristics of bacterioplankton (bacterial production P_b and destruction of organic matter R_b, as well as bacterial growth efficiency BGE). The relation was determined between these parameters and the ratio of the content of suspended mineral matter M to the total organic carbon content (M/TOC). More active utilization of organic matter by bacterioplankton in the presence of OMD resulted in its positive effect on specific production characteristics of the phytoplankton.

Key words: suspended mineral matter, adsorption of dissolved organic matter, bacterial production, bacterial growth efficiency, primary production.

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Microbial communities, with bacteria and protozoa as the key component, form an intermediate step in the matter transformation from autotrophs to zooplankton [1]. Utilization of dissolved organic matter (DOM) by heterotrophic bacteria and bacteria-grazing protozoa is a significant part of the pelagic carbon cycle [2]. Unlike the classical trophic chain, the organic carbon entering the microbial “food loop” has to be present in a dissolved phase. Transfer of organic carbon to higher trophic levels via the “microbial loop” is therefore more pronounced in the ecosystems with a high DOM content. The microbial trophic network is considered the most active biotic part of an ecosystem, where regeneration and accumulation of biogenic elements occurs. Microorganisms transform 45 to 90% of the primary production. Bacteria alone assimilate 40 to 60% of the primary production as DOM [1, 3]. Due to the “microbial loop”, the biogenic elements are preserved within the planktonic community and may be repeatedly utilized by algae [1, 4].

Heterotrophic bacteria transform the natural organic matter of the dissolved phase into new bacterial biomass (P_b) and transform organic carbon into inorganic carbon via respiration (R_b). Bacterial growth efficiency (BGE = $P_b/(P_b + R_b)$), or the amount of new bacterial biomass produced per unit of assimilated organic substrate, determines the relation between bacterial production and destruction of organic matter. According to the literature data [5–11], BGE or the coefficient of energy exchange (K_2) in freshwater bacterioplankton communities vary within the range from 0.01 to 0.80. However, rather few articles deal with the factors regulating this huge range [5, 12–14]. BGE was reported to change together with bacterial production and the trophic profusion of the ecosystem. Bacterial activity and the degree of their development depend on both the DOM concentration and its qualitative composition; the latter is determined by the ratio of allochthonous and autochthonous organic matter and the rate of their influx into an aquatic environment [11, 15]. The higher the trophic profusion of the system, the higher number of organisms and their remains (detritus) it contains. Bacteria attach to detritus particles. The phase boundary provides more favorable conditions for bacteria; intense metabolism and high regenerative capacity were reported [16–18]. Organo-mineral complexes formed on the particles of suspended inorganic matter in the course of adsorption of dissolved organic matter also belong to detritus (organo-mineral detritus, OMD). Acceleration and activation of the processes of biogenic matter transformation on the surfaces result in increased bacterioplankton productivity at high contents of suspended matter [19–22]. High mineralization rates of organic matter by bacterioplankton lead to increased supply of biogenic elements for planktonic algae and thus to increased phytoplankton production [21, 23, 24].

The goal of the present work was to assess the effect of organo-mineral detritus on the development of bacterioplankton and phytoplankton in aquatic objects with different levels of suspended mineral matter.

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Limits of variation (average values) of the measured characteristics in the water bodies under investigation

Parameter	Water body		
	Khanka Lake	Yenisei River	Krasnoyarsk Reservoir
N, 10^6 cells/ml	0.70–5.38 (2.05)	0.60–2.50 (1.80)	1.00–2.70 (1.70)
P_b, mg C/ml	0.02–0.19 (0.07)	0.02–0.16 (0.05)	0.01–0.08 (0.03)
R_b, mg C/ml	0.02–0.45 (0.12)	0.08–0.70 (0.23)	0.03–0.53 (0.17)
P_b/B_b, day^{-1}	0.20–1.80 (0.75)	0.22–1.62 (0.76)	0.09–0.80 (0.38)
g, h	9–83 (28)	9–73 (29)	20–185 (51)
BGE	0.08–0.69 (0.37)	0.09–0.43 (0.22)	0.04–0.50 (0.15)
M, mg/l	8.5–130.0 (47.0)	1.4–55.0 (3.7)	0.9–4.8 (2.3)
M/TOC, mg/mg C	0.5–52.0 (16.0)	0.2–9.0 (2.4)	0.8–6.3 (2.9)
POC, %	27–86 (78)	8–31 (24)	16–29 (23)
B_{ph}, mg/l	0.03–1.59 (0.22)	1.5–19.0 (0.67)	0.6–32.0 (0.38)
P_{ph}/B_{ph}, day^{-1}	4.4–60.0 (22.0)	1.5–19.0 (9.0)	0.6–32.0 (7.0)

MATERIALS AND METHODS

The data for comparative analysis were obtained during research on Khanka Lake and its tributaries (1995, 1996, and 1998), the Yenisei River (1994 and 1997), and the Krasnoyarsk Reservoir (2000 and 2001).

Khanka Lake is a system functioning in the presence of a high number of fine-dispersed terrigenous particles, similar to Lake Chapala [19, 25]. In spite of light limitation (Secchi disk transparency is 15 to 18 m), water bodies of this type are highly productive and carry significant anthropogenic loads. The amount of suspended mineral matter in the Yenisei River and in the Krasnoyarsk Reservoir is significantly lower.

Total bacterial numbers (N) were determined by direct microscopy after fluorescamine staining [26] and precipitation on Sudan black B-treated 0.17-μm track filters. The cells were counted under an ML-2B microscope in 20 microscope fields at ×1500 magnification. The generation time (g, h) and bacterial production (P_b) were determined by direct count as changes in cell number (N) or biomass (B_b) during a specified time interval in two isolated water samples; consumers were removed from one sample by filtration through 4.5-μm filters [27–29]. Primary production of phytoplankton (P_{ph}) and total destruction of organic matter (D) were determined by the oxygen modification of the bottle method [29]. Bacterial respiration (R_b) was determined from the average values of the R_b percentage to the total destruction of organic matter [11]. Simultaneous determination of bacterial production and their expense for respiration enables determination of BGE (bacterial growth efficiency) [28].

Dissolved total organic carbon (TOC) was determined by the optical method as changes in the chemical consumption of oxygen and by fluorescence of the water samples [30]. The content of suspended mineral matter M was determined by total light scattering [30].

The pool of total organic carbon (TOC) consists of two fractions: dissolved organic carbon (DOC), i.e., the fractions passing through a 0.2 μm filter and particulate organic carbon (POC). DOC content was determined by light adsorption in the filtrates. POC is formed in the course of physical and chemical processes from dissolved organic matter; it consists of colloidal fractions (COC) and of those adsorbed on the particles of suspended mineral matter (AOC). Although the separation of the two latter fractions is impossible, a strong correlation should be mentioned between the POC content and the content of suspended mineral matter. This suggests that small mineral particles are either captured by colloidal particles or act as centers of formation for colloidal particles.

RESULTS AND DISCUSSION

The characteristics in the water bodies under study varied in a rather broad range (table). The water bodies differ significantly from each other in most of the parameters. However, the main reason these objects were chosen for analysis is the difference in the content of suspended mineral matter and its ratio to the total dissolved organic matter M/TOC.

In [22], a model experiment was carried out with a humic acids solution as an organic matter and different concentrations of kaolin as suspended matter. The effect of the mineral suspension on the bacterial growth efficiency (BGE) was revealed. The BGE values in the control samples and in those supplemented with kaolin suspensions were comparable only on the first day and by the end of the tenth day. In all other cases, BGE values for the samples supplemented with the mineral suspension were higher than in the control. Among other things, this is an indication of the differences in population ageing in the presence and absence of the suspension.

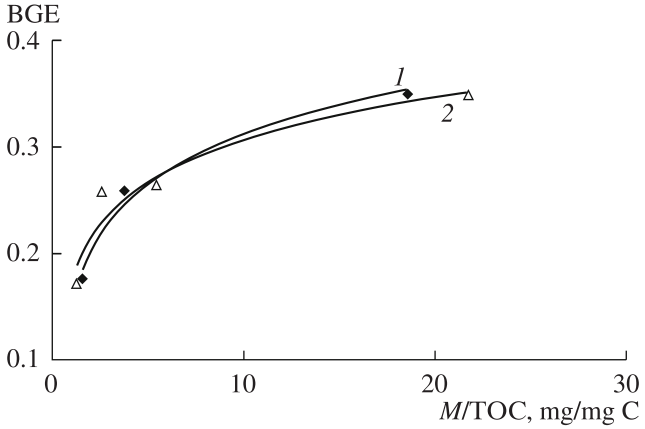

Fig. 1. Dependence of bacterial growth efficiency on the ratio between the content of suspended mineral matter and the total organic carbon content: subdivision into 3 zones (18 samples each) (*1*) and into 4 zones (13, 13, 14, and 14 samples) (*2*).

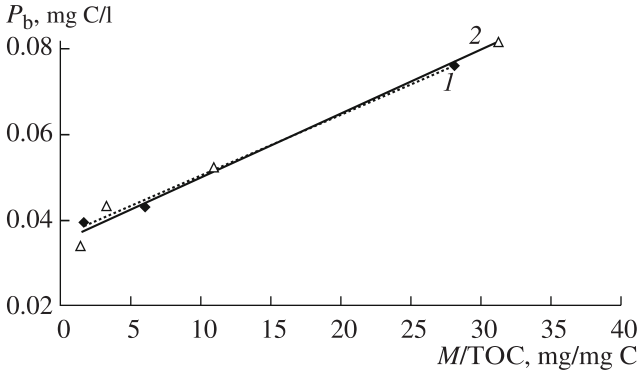

Fig. 2. Dependence of bacterial production on the ratio between the content of suspended mineral matter and the total organic carbon content: subdivision into 3 zones (23 samples each) (*1*) and into 4 zones (17, 17, 17, and 18 samples) (*2*).

In the investigated water bodies, BGE values were related to the *M*/TOC ratio. The *M*/TOC values varied from 0.2 to 52 mg/mg C; the BGE values, from 0.04 to 0.60. Logarithmic regression for the overall data set including Khanka Lake, the Yenisei River, and the Krasnoyarsk Reservoir is expressed by the following equation: BGE = 0.06 Ln (M/TOC) + 0.18 (r = 0.55; number of samples = 54). The variation of BGE values is too broad (and the correlation coefficient is correspondingly too low) to evaluate the validity of the trend of its changes depending on the *M*/TOC ratio. This is understandable, since the measurements were taken in different water bodies, in different years, and under highly different conditions. For smoothing the effect of numerous other factors influencing bacterioplankton growth and development, let us carry out the averaging by dividing the ranged row of the *M*/TOC values into zones with equal numbers of experiments; for verification, let us divide it into 3 and 4 zones. The average values of the argument and BGE are then calculated (Fig. 1). The trends built using the calculated values practically coincide with the trend built using all experimental points: BGE = 0.06 Ln (M/TOC) + 0.18 (r = 0.95; 4 zones) and BGE = 0.07 Ln (M/TOC) + 0.16 (r = 0.99; 3 zones). This is an evidence of good confidence of the logarithmic regression. The median centers method, which is usually applied in cases of pronounced data scattering, results in a similar regression equation: BGE = 0.06 Ln (M/TOC) + 0.16 (r = 0.92; 4 zones). Thus, it can be confidently stated that the BGE increases with an increasing amount of mineral organic matter per TOC unit. Subdivision of the set into 3 zones (with more experimental data per each of the three points) results in an increased regression coefficient; this is an indication of a more pronounced leveling of other factors affecting the bacterial growth.

Increased growth efficiency results primarily from the anabolic reactions, i.e., from utilization of an organic substrate for biomass synthesis. Linear approximation of the dependence between bacterial production and the *M*/TOC value is expressed by the following equation: P_b = 0.0015 (M/TOC) + 0.035 (r = 0.62; 69 samples). The trends for the averaged values almost coincide with this ratio: P_b = 0.0014 (M/TOC) + 0.036 (r = 0.99; 3 zones, 23 samples in each) and P_b = 0.0015(M/TOC) + 0.035 (r = 0.99; 4 zones, 17 samples in each) (Fig. 2). Due to a higher content of suspended mineral matter, the average value for the bacterial production of Khanka Lake is 1.4 times higher than in the Yenisei River and 2.3 times higher than in the Krasnoyarsk Reservoir.

The net bacterial respiration is not affected significantly by the ratio between the content of suspended mineral matter and the content of total organic carbon (*M*/TOC); the correlation coefficient between R_b and *M*/TOC determined for experimental data was r = 0.2 (77 samples). This may be due to the fact that in Khanka Lake, higher bacterial numbers were found, while the respiration values per cell were the lowest. For example, the values of respiration per cell (R_b/N) in the Yenisei River, the Krasnoyarsk Reservoir, and the Khanka Lake were 0.14, 0.06, and 0.05 pg C/cell, respectively.

The respiration value per cell decreases with an increasing ratio of suspended mineral matter to the total organic carbon content. For the averaged values of *M*/TOC and R_b/N, the power dependence provides the best correlation between the parameters (Fig. 3). Regression using the averaged data: $R_b/N = 0.12(M/\mathrm{TOC})^{-0.35}$ (r = 0.98; 3 zones) and $R_b/N = 0.12(M/\mathrm{TOC})^{-0.32}$ (r = 0.93; 4 zones) coincide well with

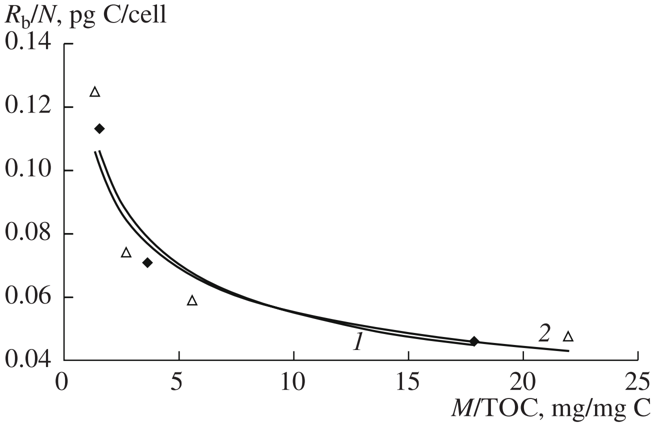

Fig. 3. Effect of the ratio between the content of suspended mineral matter and the total organic carbon content on bacterial respiration per cell: subdivision into 3 zones (*1*) and into 4 zones (*2*).

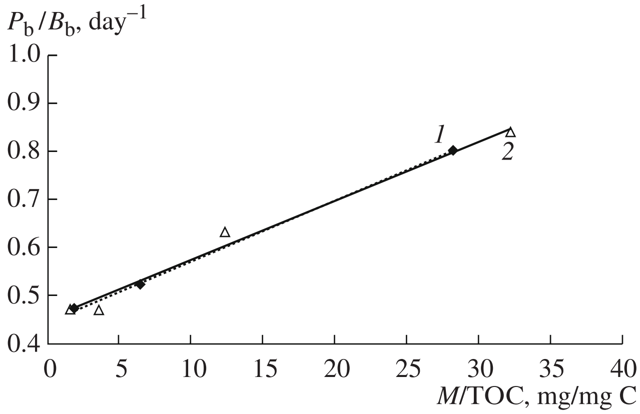

Fig. 4. Dependence between specific bacterial production and the M/TOC ratio: subdivision into 3 zones (*1*) and into 4 zones (*2*).

the trend for the complete set of experimental data: $R_b/N = 0.10\ (M/\text{TOC})^{-0.35}$ ($r = 0.55$). This may mean that under increased content of colloidal (COC) and adsorbed (AOC) fractions of organic matter, bacterioplankton is able to decrease substrate consumption for catabolic reactions not directly related to building up the biomass.

Specific bacterial production (P_b/B_b, day^{-1}) also increases with an increase in the M/TOC ratio (Fig. 4). Linear regression for the averaged P_b/B_b values are expressed by the following equations: $P_b/B_b = 0.0122\ (M/\text{TOC}) + 0.45$ ($r = 0.99$; 4 zones) and $P_b/B_b = 0.0125\ (M/\text{TOC}) + 0.45$ ($r = 0.999$; 3 zones); they conform well to the regression using all experimental data: $P_b/B_b = 0.014\ (M/\text{TOC}) + 0.43$ ($r = 0.55$; 64 samples). The line obtained by the median centers method lies somewhat lower: $P_b/B_b = 0.011(M/\text{TOC}) + 0.39$ ($r = 0.96$; 4 zones).

Our research supports the conclusion that the surface boundary of organo-mineral detritus plays a significant role in the functioning of aquatic ecosystems. For example, application of the Student criterion (t_{st}) for comparison of specific primary production reveals significantly higher values ($t_{st} = 3.98$ vs. $t_{st\ (table)} = 1.92$) for the Khanka Lake (22.0 day^{-1}) than for the Yenisei River and the Krasnoyarsk Reservoir (9.0 and 7.0 day^{-1}, respectively). Since bacteria virtually do not precipitate and retain the biogenic elements within the planktonic community, their high assimilatory potential facilitates rapid recycling of biogenic matter, thus making it repeatedly available to the phytoplankton.

Organo-mineral detritus affects bacterial growth and stimulates their productivity and transformation of organic matter to biogenic elements. This should affect the production characteristics of the phytoplankton. We have previously demonstrated [31] using the multifactor model that a twofold increase of bacterioplankton production (at the constant values of other parameters) resulted in an increase in primary production in the Khanka Lake, the Yenisei River, and the Krasnoyarsk Reservoir by 2.5, 1.9, and 1.4-fold, respectively. An increase in primary production may be explained by enhanced bacterioplankton activity, since phytoplankton production increases with an increased amount of food energy assimilated by bacteria ($P_b + R_b$). The equation of linear regression for the averaged values is as follows: $P_{ph} = 0.79\ (P_b + R_b) + 0.03$ ($r = 0.96$). Effect of bacterioplankton on the production characteristics of phytoplankton is confirmed by the fact that an increase of specific bacterial production results in an increase of specific primary production (Fig. 5). In order to demonstrate the difference in specific primary production caused by high concentrations of suspended mineral matter, the dependences for the Khanka Lake, the Yenisei River and the Krasnoyarsk Reservoir are presented individually. They are approximated by the fol-

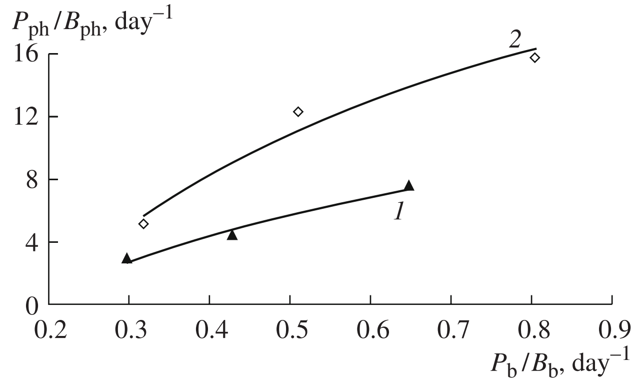

Fig. 5. Dependence between specific primary production and specific bacterial production: subdivision into 3 zones (*1*) and into 4 zones (*2*).

lowing logarithmic expressions: P_{ph}/B_{ph} = 5.9 Ln (P_{ph}/B_{ph}) + 9.9 ($r = 0.98$; the Yenisei river and the Krasnoyarsk Reservoir) and P_{ph}/B_{ph} = 11.4 Ln(P_{ph}/B_{ph}) + 18.8 ($r = 0.98$; the Khanka Lake). For the complete data set, the regression equation is as follows: P_{ph}/B_{ph} = 7.1 Ln (P_{ph}/B_{ph}) + 13.4 ($r = 0.998$).

Thus, an increased content of suspended mineral matter was demonstrated to have a direct effect on the characteristics of bacterioplankton production and to affect the characteristics of phytoplankton production due to an improved supply of biogenic elements.

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