The role of nitrogen-phosphorus ratio in selecting for dominance of phytoplankton by cyanobacteria or green algae and its application to reservoir management

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Abstract

The undesirable consequences of phosphorus enrichment in reservoirs are primarily connected with the emerging abundance of cyanobacteria which are not utilized by the consumers and form, as a rule, a trophic block in the majority of nutrition chains. Blooming of *Chlorococcales* does not produce these negative effects since they are actively consumed by grazers.

The N:P ratio turns out to be the factor which regulates the dominance of planktonic communities by blue-green or green microorganisms. Decrease of the N:P ratio, through the addition of phosphorus compounds, leads to cyanobacterial blooming.

In order to replace blue-green dominance of eutrophic reservoirs by dominant greens, it is suggested that the addition of nitrogen, thus varying the N:P ratio (nutrient manipulation) to apply, is superior to the traditional phosphorus load decrease. Utilization of the redundant green algal biomass may occur in a natural way or be conducted with the aid of biomanipulation, i.e., by introduction of planktivorous fish into the reservoir.

1. Introduction. Causes and consequences of reservoir blooming

The anthropogenic enrichment of natural waters by mineral nutrients and the growth of algae (eutrophication) lead to waterquality changes which are undesirable from the standpoint of many aspects of water management: for everyday life, recreation, fish breeding, power engineering, etc. In particular, reservoir eutrophication is causes by the increased concentration of phosphorus compounds in affected waters (Vollenweider, 1971; Sirenko & Gavrilenko, 1978).

A typical consequence of reservoir eutrophication is the explosive blooming of blue-green algae (cyanobacteria), with subsequent die off to their excessive biomass, with toxin production and oxygen consumption. Moreover, accumulation of excessive blue-green biomass in the course of reservoir eutrophication is connected with the fact that the majority of taxa of cyanobacteria create a blockage in pelagic food chain. Indeed, the crustaceans in the zooplankton scarcely eat the large colonial and filamentous blue-green species (Gusynskaya, 1978; Hanazato & Yasumo, 1988). Attaining a high biomass, the cyanobacteria may also exclude planktonic crustaceans through toxin production (Haney, 1987; Lampert, 1987).

A similar tendency is observed in the nutrition of herbivorous fish. The blue-greens are, as a rule, avoided by silver and motley carp due to the poor nutritional value of the food and even to their toxicity. It is believed (Maliarevskaya, 1973; Topachevsky *et al.*, 1975) that even if a plantivorous fish ingests blue-greens, they are weakly digested and poorly assimilated. Whereas small species of cyanobacteria still are consumed by fish, the filamentous species (*Phormidium, Oscillatoria, Aphanizomenon*) are nutritionally unsuitable (Danchenko, 1974).

A standard way of overcoming the eutrophication which leads to blue-green algae dominance is to reduce the phosphorous load on the reservoirs. However, this is not always practicable, since the source of phosphorous compounds are often diffuse, numerous and diverse, and so difficult to control. Standard methods of overcoming the consequences of eutrophication include the chemical methods of phosphorus compounds sedimentation (Safferman, 1963) and the physio-chemical methods for overcoming the presence of blue-greens: mechanical biomass removal, aeration of huge areas of lake, application of algicidal preparations, coagulating agents and *in situ* ultrasonics (Komarenko & Vasilyeva, 1972; Schmidt, 1973; Bumbu *et al.*, 1974, 1978). All these methods, at the scale of appliion, expensive and inefficient, while algicidal preparations, if applied, unfavourably affect the life of other aquatic biota.

2. Blue-greens blooming mechanisms

We would like to note two possible mechanisms which may lead to blue-green dominance as a consequence of phosphorus abundance.

The first one is connected with the exclusive ability of some taxa of cytanobacteria to fix free nitrogen dissolved in water (Carpenter & Price, 1976; Bryceson & Fay, 1981; Bothe, 1982).

When phosphorus salts are present in excess, the development of algae is restricted by nitrogen compounds and an absolute advantage is gained by the taxa of nitrogen-fixing genera. In other words, non-nitrogen-fixing organisms (greens, diatoms, euglenids and some species of blue-greens) grow in proportion to the limits of the low nitrogen resources, while the nitrogen-fixing cyanobacteria may grow in proportion to the phosphorus supply.

The second mechanism of dominance by non-nitrogen-fixing blue-greens may be connected to the low nitrogen-to-phosphorus ratio said to be optimal for the growth of the blue-greens.

That a low N:P ratio is advantageous to blue-greens is indicated, in particular, by an analysis of models of mathematical ecology (Levich & Lebed', 1987; Levich, 1989; Levich & Lichman, 1992; Levich *et al.*, 1993). As may be deduced from the analysis, the nutrient-concentration ratios which are optimal for different microalgal groups are close to the ratios of cellular requirements in these substances for each of the groups considered.

The unambiguous effect of the nitrogen-to-phosphorus ratio an different microalgal taxa has been proved in a number of empirical studies of natural and laboratory phytoplankton.

The results of our own experiments on accumulative pond phytoplankton cultivation in vitro (Levich *et al.*, 1992) have shown that a change of the initial nitrogen-to-phosphorus concentration ratio causes a change in the eventual dominance.

The experiments with natural phytoplankton have been stages under controlled conditions. For that purpose the water from a fish-breeding pond (Astrakhan region) was placed in five 2-liter flasks, where afterwards NH_4NO_3 and $Ca(H_2PO_4)_2$ were added in different quantitative combinations (N:P = 2, 5, 20, 50, 100). The initial biomass were the same in all the aquaria. To prevent the effect of eating-out by zooplankton the water to be used in the experiment was let through a cellular net with the corresponding cell size and left for two days in the darkness. All the aquaria during the whole experiment were kept out of doors. The abundance and, simultaneously, masses of phytoplankton cells (the latter by measuring individual size) were determined under a microscope. The obtained biomass served as the basic functional parameter for different systematic groups. The observations of algal growth dynamics were conducted within 14 days.

Figure 1 shows the outcome of the biomass of algal divisions at the stationary growth stage (i.e., when cell division has stopped) on the initial environmental nitrogen-to-phosphorus ration. Absolute domination of the greens coincides with ratios greater than five appreciably. The dependence curve of algal biomass vs. nitrogen-to-phosphorus ratio for the greens has a single peak at the ratio equal to 20, which corresponds to the most rapid growth. For the diatoms and blue-green algae a maximum biomass is achieved at low ratios (from two to five). Non-nitrogen-fixing ones were predominant among the cyanobacteria. This leads to the conclusion that it was not the absolute amount of nitrogen that affected the improvement or worsening of their growth conditions, but the environmental nitrogen-to-phosphorus ratio. Other authors' data also indicate that the blooming of the blue-greens and other divisions of phytoplankton from natural reservoirs can be successfully regulated by varying the ratios of mineral nutrition components (Suttle & Harrison, 1988; Wilcox & De Costa, 1990). Although other points of view certainly exist as well. I would remark
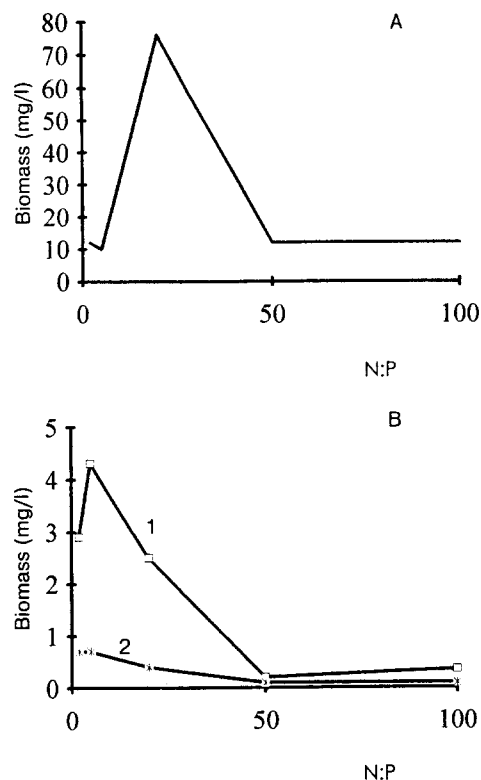
Figure 1. The dependence of ultimate biomass of phytoplankton divisions on the initial nitrogen-to-phosphorus ratio. A - *Chlorophyta*; B - *Bacillariophyta* (1); *Cyanophyta* (2).

that the absolute amounts of nitrogen and phosphorus certainly determine the total biomass of the community species. The N:P ratio determines the fraction of this biomass belonging to a specific (taxonomic or size) group of organisms. Thus the N:P ratio affects the partial biomass of phytoplankton groups. If the total biomass of the community is fixed, then the N:P ratio determines the absolute biomasses of selected groups of cells.

The experiments in which nitrogen and phosphorus compounds were added to ponds in different quantitative combinations permit us to consider the possibility of artificially regulating blooming in natural conditions as well (Levich & Bulgakov, 1992).

Such experiments were conducted in 1987–89 on experimental fish ponds situated in the Lower Volga region. The phosphate and nitrogen fertilizers were introduced into the ponds in certain proportions from April to September under two schedules: experimental (N:P = 20–25) and control (N:P = 4) ones. Phytoplankton samples were taken from April to September in all ponds once

in every ten days. The samples were settled for 7–10 days and, after seston settlement, the upper layer of water was poured out with the use of siphon, while remaining concentrated volume (30–50 ml) was used for quantitative analysis of phytoplankton. The cell quantity and individual cell volumes were estimated in Najotte camera using dissecting microscope. Cell volumes were calculated by approximation to the nearest simple geometric solid (sphere, cylinder, ellipsoid, etc.) after measurement of no less than 50 cells of each species. The average individual mass for every species was obtained by multiplying the cell volume value by density of 1 g/cm^3. Then the total biomass of phytoplankton species, genera, orders and divisions were estimated. The species and genera with biomass comprising no less than 20% of the total phytoplankton biomass in at least 5 arbitrary sampling dates (out of 15–20 samples in a season) were regarded as leading ones, and only these species were analysed. To analyse the size community structure, all phytoplankters were categorized according to their individual size (in mass units). The biomass in samples was calculated for the following size classes: less than 0.1 ng; 0.1–0.3 ng; 0.3–1 ng; 1–3.2 ng; 3.2–10 ng; more than 10 ng.

Figures 2 and 3 show the seasonal dynamics of biomass of the *Chlorococcales* and *Cyanophyta* in experimental and control ponds. The nitrogen-to-phosphorus ratio was, on average throughout the season, about 4 in the control ponds and 25 in the experimental ones. It turned out that, as the nitrogen-to-phosphorus ratio got higher, the biomass of the *Chlorococcales* increased while that of the cyanobacteria decreased. Just as in the experiments *in vitro*, stimulation of the blue-greens at low N:P ratios takes place at the expense of the species incapable of nitrogen fixing.

Comparison with numerous data sets from the world lakes (Schindler, 1977; Smith, 1983; Varis, 1991) confirms the conclusion that the blue-greens are most viable at lower nitrogen-to-phosphorus ratios than are, for instance, the green algae. This enabled Tilman (1982) to call the discovered law a dramatic influence of such a factor as nitrogen-to-phosphorus ratio on the taxonomic composition of lake algocoenoses. See also the works of Findley & Kasian (1987), McQueen & Laan (1987), Stockner & Shortreed (1988), Cho *et al.* (1990) and Haarhoff *et al.* (1992).
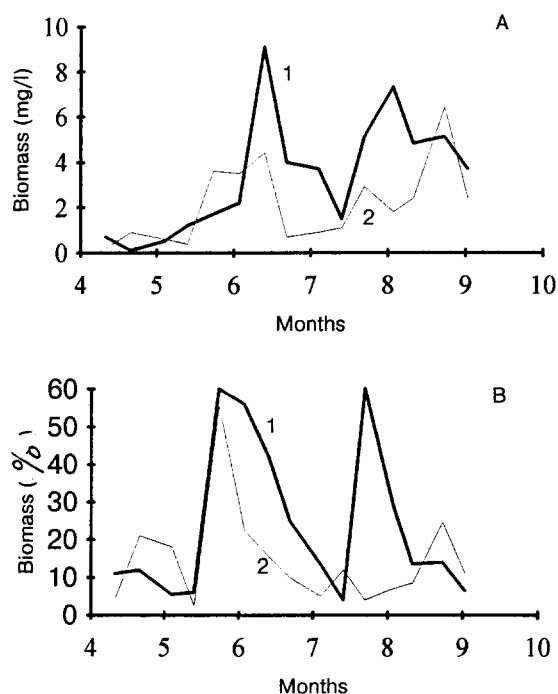
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Figure 2. Dynamics of the biomass (A) and percent of biomass (B) of *Chlorococcales*: 1 – experiment, 2 – control.
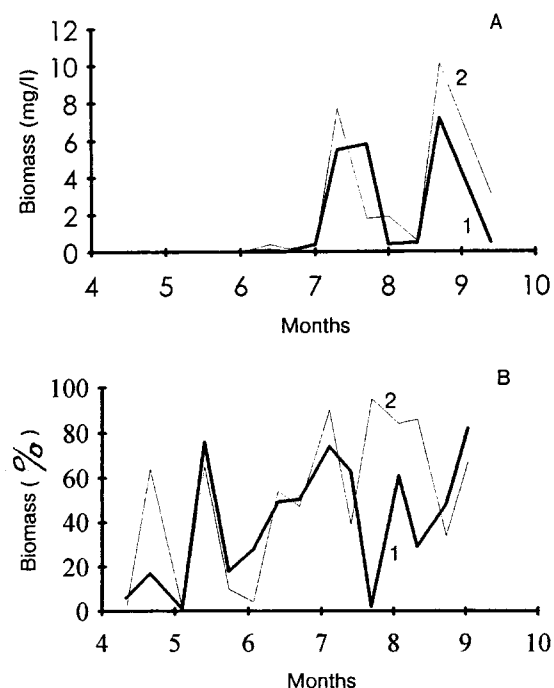

Figure 3. Dynamics of the biomass (A) and percent of biomass (B) of *Cyanophyta*: 1 – experiment, 2 – control.

Regulation of species composition by N:P ratio is observed also in laboratory experiments using artificial communities (Suttle & Harrison, 1988; Levich & Bulgakov, 1993).

3. Ecological approaches to blooming type regulation in eutrophic reservoirs

The suggested ecological way of getting rid of the excessive production of trophically useless cyanobacteria resulting from phosphorus concentration involves two steps of ecosystem control. The first stage, nutrient manipulation, consists of increasing the nitrogen-to-phosphorus ratio in the water of the eutrophicated reservoir. The uncommonness of this method is that the necessary increase is achieved not at the expense of phosphorus extraction but at the expense of addition of nitrogen compounds to the eutrophicated reservoir. As shown by our model and experimental studies, at certain values of the nitrogen-to-phosphorus ratio, nutrient manipulation suppresses the cyanobacterial blooming and leads to dominance by the *Chlorococcales*.

The second stage of the control, biomanipulation, consists in introducing planktivorous fish to the reservoir, to transform the redundant primary production of the actively consumed *Chlorococcales* to the secondary production of fish. For this purpose it is reasonable to put into operation the rational fish-breeding reservoir-fertilizing system, according to which silver and motley carp are introduced in the ponds (Levich *et al.*, 1995).

This system was tested on fish ponds in the Lower Volga region in 1987–89. The differences in the methods of fertilization in standard (control) and rational (experiment) systems are presented in Table 1. In the control ponds, the lump doses of fertilizers were the same throughout the season and corresponded to 2 mg/l of nitrogen and 0.5 mg/l of phosphorus concentration in the water. In the experimental ponds, the doses of fertilizers varied depending on the phytoplankton production observed in certain time of vegetative season. Thus, the doses were correlated with the dynamics of biomass of herbivores, with their daily food intake as well as with phytoplankton requirements for nitrogen and phosphorus. The nitrogenous and phosphate fertilizers were applied in the form of NH_4NO_3 and $Ca(H_2PO_4)_2$. These substances were

Table 1. Fertilization pattern in experimental and control ponds

Elements of fertilization system	1987		1988		1989	
	Experiment	Control	Experiment	Control	Experiment	Control
Nitrogen quality applied in a season, 10^{-4} kg/m^2	563	195	382	134	450	267
Phosphorus quality applied in a season, 10^{-4} kg/m^2	16	48	39	34	11	67
N:P weight ratio in applied fertilizers averaged over a season	35	4	10	4	41	4
N:P weight ratio in applied fertilizers before the fish stocking	–	–	4	–	23	–
Interval between inputs of fertilizers, days	8	12	4	11	4	10
Beginning of fertilization	April		May		April	
	17	17	1	10	4	17

Remark: Symbol "–" signifies that fertilization was begun after the fish stocking.

simultaneously introduced into the ponds from a boat, but they were not mixed were distributed evenly over the whole pone area. The nitrate was poured into the water at once, while the super-phosphate was at first soaked and then poured into pond in the watery consistence. The control and experimental ponds were stocked by young of carp *Cyprinus carpio*, silver carp *Hypophthalmichthys molitrix* and motley carp *Aristichthys nobilis*. During the season fish grew on the average from 30 to 500–700 g. The fish density was approximately the same in the control and experiment and varied from season to season within the limits of 500–4000 individuals per ha for silver carp, 300–1000 individuals per ha for motley carp, and 2000–6000 individuals per ha for carp. Fish stocking in ponds was performed in the middle of April. In 1988–89, the fertilization of experimental ponds began two weeks before the fish stocking to provide the necessary phytoplankton biomass by the stocking time. A trial of this system in fish breeding ponds has demonstrated the high efficiency of the above measures. The productivity of planktivorous fish in the experimental ponds was 19 percent higher than in the ponds fertilized according to the norma-tive technology, while the total fish production, including carp, silver carp and motley carp was 16 percent higher. Herewith the excess the nitro-gen added to the water did not lead to an excess of nitrogen compounds (nitrates, nitrites, etc.) in fish tissues. The salt contents were equal in the fish from both the experimental and control ponds and did not exceed the upper bound prescribed by the state sanitary standard.

Introduction of herbivorous fish is not the only way of utilizing the excessive (due to eutrophication) green algal biomass. The green cells are actively consumed by desirable zooplankton, which, in turn, serves as food for predators, so that the primary production, in proportions common to trophic pyramids, is trans-formed to the final levels of the pasture and detrital-food chains of the reservoir. That is why there are no catastrophic consequences of stormy blooming of reservoirs with green, diatomic and other actively con-sumed algae: the algal blooming peak is followed by zooplankton abundance peaks, etc. Thus, unlike the cyanobacteria, the biomass of consumed algae is not accumulated and does not readily decay. This is the reason why the paradoxical addition of nitrogenic forms of nutrients to a reservoir rich in phosphorus does not aggravate the undesirable consequences of eutrophication (reservoir poisoning, oxygen defici-ency).

The suggested blooming-regulation methods (changing of the domination of blue-green by that of green algae) are applicable for recreation reservoirs, cooling reservoirs and those for drinking and other

usage. Nutrient manipulations may play a specific role as elements of a rational ecology-based fertilizing system (Levich *et al.*, 1995) for fish-breeding reservoirs, especially with fish polyculture including herbivorous fish.

These are situations when the opposite direction of blooming regulation is desirable. The case in point is that of accumulating reservoirs for unpurified domestic and zoological sewage which could be used for agricultural crops watering after biological purification. Low nitrogen-to-phosphorus ratio (due to added phosphorus compounds) leads in such reservoirs to cyanobacterial blooming. The cyanobacteria, due to their biocidal (bactericidal, fungicidal, *etc.*) properties (Jakob, 1957; Ramaurthy & Seshadri, 1986; Kozhevnikov *et al.*, 1972; Mason *et al.*, 1982; Gleason & Paulson, 1984; all citations with Sirenko & Kozitskaya, 1988) are sufficiently capable of conducting disinfection of sewage from poultry plants, animal farms, some kinds of animal husbandry complexes and communal services. The toxins of the majority of blue-green algae exhibit a wide spectrum of antimicrobial action in comparison to representative of saprophyte and pathogenic microorganisms. At high toxin concentrations the saprophyte bacteria are suppressed, as well as pathogenic microorganisms (salmonella, staphylococci) and helminthal eggs (Kirpenko *et al.*, 1977).

An excess of cyanobacteria in irrigation water can positively affect the development of agricultural crops, in particular, cotton. Irrigation of soils with water rich in phytoplankton improves their biological state (oxygen supply, fixation of nitrogen and humic substances in the soil, its enrichment with proteins, vitamins, auxins, microelements, indispensable aminoacids, mineral salts); the struggle against root putrescence is more successful, the cotton morbidity is lowered (Muzafarov *et al.*, 1984). Some species of the cyanobacteria are able to produce metabolites which stimulate the germinating capacity of cotton, wheat and rice seeds and the growth of adult individuals (Kasymova *et al.*, 1984; Krasnianskaya *et al.*, 1984).

Acknowledgements

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