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Research Article

**ANNUAL SUCCESSION PATTERNS OF BLUE-GREEN ALGAE AS  
RELATED TO PHYSICOCHEMICAL WATER PARAMETERS IN THE  
URBAN LAKE JEZIORAK MAŁY IN THE 1998 – 2003 PERIOD**

ELŻBIETA ZĘBEK

*University of Warmia and Mazury  
Żołnierska 14c, 10-561 Olsztyn, Poland  
phone: 048(89)5246067  
e-mail: elzbieta.zebek@uwm.edu.pl*

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**Abstract**

Studies on net phytoplankton were conducted in the urban Lake Jeziorak Mały (Mazurian Lakeland) in the 1998-2003 period. Changes in the numbers of blue-green algae were analyzed in the annual cycle with respect to water temperature and orthophosphate concentration. An increase in water temperature above 13°C was followed by an increase in the population density of blue-greens. Two abundance peaks of blue-green algae were recorded in the summers of 1998, 1999, and 2002 and one in the summers of 2000, 2001, and 2003. The coefficient of correlation between water temperature and the occurrence of blue-greens was statistically significant, but no statistically significant correlation was found between orthophosphate concentration and the abundance of blue-green algae. From May to August, under conditions of the domination of blue-green algae (over 50% of the total phytoplankton biomass) and water temperature exceeding 19°C, this correlation was negative and statistically significant. This suggests that over this period the blue-greens could contribute to reducing the concentration of orthophosphates in the water.

## INTRODUCTION

Ecological succession is an orderly process of directional changes in the biocenosis, in which a community of living organisms replaces the previous one over time. The process is also observed at the level of planktonic algal communities (Wiśniewski and Kowalewski 2000). Lampert and Sommer (1996) give a wider definition of succession. According to these authors, succession is an orderly process of directional changes in the species structure of the biocenosis, which may proceed for several hundred, or even several thousand years (*e.g.*, lake freezing over), or which may be a regular and repeatable sequence of changes in the biocenosis resulting from cyclical environmental changes (*e.g.*, annual plankton succession). Ecological succession can be divided into allogenic, driven by external environmental forces (*e.g.*, climate changes), and autogenic, driven by the organisms themselves, where the process of replacing previous occupants by new ones is dependent upon the activity of other organisms altering the habitat (*e.g.*, nutrient depletion).

The development of phytoplankton is often described on the basis of annual succession patterns (Sommer *et al.* 1986, Reynolds 1993, Mayer *et al.* 1997, Noges and Laugaste 1998, Nixdorf 1994). It is determined by numerous factors, such as seasonal changes in water temperature or solar radiation, or the mixing and resuspension of biogenic elements, including phosphorus, from sediments (Hutchinson 1967, Sommer *et al.* 1986 as cited in Findenegg 1943).

The inflow of nutrients, mainly phosphorus, results in changes in the domination structure of phytoplankton taxonomic groups in water bodies over the year. Green algae are the predominant group when nutrient amounts are low. Planktonic algae are then grazed upon by zooplankton and other aquatic organisms. Under conditions of nutrient abundance, phytoplankton communities are dominated by the blue-greens, and the system organization is determined by competition (*e.g.*, for nutrients) (Krebs 1996). Such a situation is typical of strongly eutrophic lakes.

An example of a strongly eutrophic water body, where phytoplankton communities are dominated by the blue-greens over the year, is the urban Lake Jeziorak Mały. The aim of the present study, conducted in the 1998-2003 period, was to determine changes in the numbers of blue-green algae in the annual cycle, as related to water temperature and orthophosphate concentration.

## MATERIALS AND METHODS

The urban Lake Jeziorak Mały covers a total area of 26 ha; its maximum depth is 6.4 m at a mean depth of 3.4 m and a water volume of 891 000 m<sup>3</sup>. For

many decades the lake received inputs of municipal sewage from the town of Iława. Since 1991, the effluents have been treated at a local wastewater treatment plant, and since 1997 restoration works have been carried out in the lake, including the installation of separators for the pretreatment of storm water influents, and a fountain-based water aeration system.

Samples were collected once a month from April to October in the 1998-2003 period at six sites located in the littoral zone. The samples were taken with a 10 dm<sup>3</sup> calibrated bucket (20l at each site), poured through a no. 30 plankton net and preserved with Lugol's solution and then with a 4% formaldehyde solution. A total of 228 samples were taken.

The following physicochemical water parameters were determined: air and water temperature (°C); oxygen content (mg O<sub>2</sub> dm<sup>-3</sup>) with an HI 9143 oxygen meter; water pH with a Checker pH-meter; electrolytic conductivity (μS cm<sup>-1</sup>) with a CONMET 1 conductometer; orthophosphate concentration (mgPO<sub>4</sub> dm<sup>-3</sup>) with an HI 93713 HANNA colorimeter; Secchi disk transparency (m).

Quantitative and qualitative determinations of blue-greens were performed under an Alphaphot YS2 NIKON optical microscope, at magnifications of 10x, 20x, 40x, and 60x. The microscope was coupled (via a camera) to a computer with the MultiScan program. Computer images were printed with a MINOLTA laser printer. The specimens were counted in a 1 ml plankton chamber, and their number is given per dm<sup>3</sup>.

The Pearson correlation coefficient was applied in order to determine the statistical significance of relationships between water temperature and the numbers of blue-green algae, and orthophosphate concentration and the numbers and proportions of blue-greens in the total phytoplankton biomass (Guilford 1964, Marszałkiewicz 1972). These relationships are presented in the form of straight line regression equations. To verify the representativeness of the experimental materials collected, the following characteristics of the sets examined were calculated: standard deviation; coefficient of variation; median; modal value; coefficient of asymmetry representing distribution skewness (Guilford 1964). Arithmetic means representing the occurrence of blue-green algae in particular years of studies (from April to October) are given as the total number of specimens divided by the number of measurements. The mean values of water physicochemical parameters were calculated in the same way.

## RESULTS AND DISCUSSION

According to the objective of the study, changes in the numbers of blue-green algae in the annual cycle were analyzed with respect to selected physicochemical parameters of the water. The study was conducted in the urban

Lake Jeziorak Mały in the 1998-2003 period. The lowest mean biomass of blue-greens was observed in 1999 (10478 specimens  $\text{dm}^{-3}$ ) and the highest in 2001 (27905 specimens  $\text{dm}^{-3}$ ). The blue-green algal community was dominated by three species - *Planktolyngbya brevicellularis* (Cronberg & Komarek), *Limnothrix redekei* (Van Goor) Meffert, and *Aphanizomenon gracile* Lemm. The warmest summers, with a mean annual air temperature above 20°C, were recorded in 1999, 2000, 2001, and 2002. In 1998 and 2003, temperatures were lower at 18.7°C and 19.3°C, respectively. The mean annual water temperatures ranged from 16.7°C in 2000 to 19.0°C in 2003. There was no correlation between water temperature and air temperature. In Lake Jeziorak Mały, water from the catchment flowed through separators, thus disturbing the annual pattern of water temperature in the littoral zone. Warmer waters were supplied to the lake in spring and fall, while those in summer were cooler (Zębek 1997). No correlation was found between oxygen content and water temperature, which could have resulted from the inflow of mixed and oxygenated waters from the separators (Table 1).

The mean value of electrolytic conductivity ( $368 \mu\text{S cm}^{-1}$ ) was determined as the total concentration of ionized compounds, including orthophosphates. It was the lowest in 2003 when the mean abundance of blue-greens was high (25402 specimens  $\text{dm}^{-3}$ ) and was the highest ( $549 \mu\text{S cm}^{-1}$ ) in 2000 when the densities of blue-green algae were low (14997 specimens  $\text{dm}^{-3}$ ). The mean annual concentrations of orthophosphates varied from  $0.23 \text{ mgPO}_4 \text{ dm}^{-3}$  in 2001 to  $0.46 \text{ mgPO}_4 \text{ dm}^{-3}$  in 2002. A low level of this biogenic element was observed at the highest abundance of blue-greens (27905 specimens  $\text{dm}^{-3}$ ) and at the lowest Secchi transparency value (0.70m). High values of this parameter were recorded at a blue-green algae biomass that was twice as low (13543 specimens  $\text{dm}^{-3}$ ) and at the highest Secchi depth value (0.90 m) (Table 1).

**Table 1**

Mean annual (April - October) abundance of blue-greens and values of water physicochemical parameters in Lake Jeziorak Mały in the 1998-2003 period.

Parameters	Year	1998	1999	2000	2001	2002	2003
Number of blue-greens (specimens $\text{dm}^{-3}$ )		10978	10478	14997	27905	13543	25402
Air temperature (°C)		18.7	21.0	21.2	20.7	21.1	19.3
Water temperature (°C)		18.6	18.5	16.7	18.6	18.2	19.0
Oxygen content ( $\text{mgO}_2 \text{ dm}^{-3}$ )		7.12	7.84	6.63	7.82	5.50	9.63
pH		9.56	8.54	8.54	8.31	9.10	8.67
Electrolytic conductivity ( $\mu\text{S cm}^{-1}$ )		533	521	549	420	411	368
Orthophosphate concentration ( $\text{mgPO}_4 \text{ dm}^{-3}$ )		0.30	0.29	0.31	0.23	0.46	0.42
Secchi disk transparency (m)		0.85	0.86	0.75	0.70	0.90	0.78

The mass development of filamentous blue-greens, especially of the former genus *Oscillatoria*, is typical of nutrient-abundant water bodies (Reynolds 1973) that are subject to constant mixing and characterized by low water transparency (Zevenboom and Mur 1981, Reynolds 1993, Huszar and Caraco 1998). Jensen *et al.* (1994) reported that the blue-greens reached their maximum population density at a phosphorus concentration of  $0.1 \text{ mgP dm}^{-3}$ . Mayer *et al.* (1997) observed the peak of their development in August at a mean annual phosphorus concentration of  $0.55 \text{ mg dm}^{-3}$ , in a shallow hypertrophic lake. The analysis above and the literature cited suggest that morphometric conditions and the values of water physicochemical parameters (*e.g.*, high mean annual temperature and high orthophosphate concentration) in Lake Jeziorak Mały were conducive to the growth of blue-green algae.

An evaluation of the significance of relationships between selected physicochemical water parameters and the abundance of blue-greens was preceded by a determination of the representativeness of the experimental variables. The data included in Table 2 show that standard deviations were higher than the arithmetic mean for the numbers of blue-green species and orthophosphate concentration, and lower for water temperature. Standard deviations did not exceed the double value of the mean. The coefficients of variations, expressed as the standard deviation of the arithmetic mean ratio, were as follows: the population size of blue-green algae – 125.60%; water temperature – 25.68%; orthophosphate concentration – 160.61%. Data distributions, determined by the coefficient of asymmetry, were moderately negatively skewed for the biomass of blue-greens, and moderately positively skewed for the other variables. Thus, it was assumed that data distributions and variation are close to normal and monomodal (Guilford 1964).

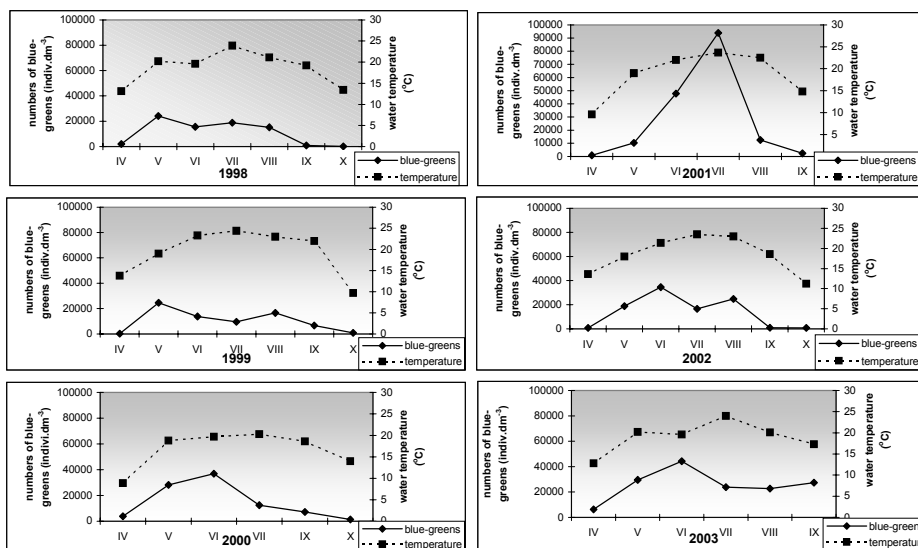
**Table 2**

Characteristics of datasets in terms of the representativeness of the experimental materials collected in Lake Jeziorak Mały in the 1998-2003 period.

Variable	Number of measurements (N)	Mean (X)	Standard deviation ( $\delta$ )	Coefficient of variation (V) %	Median (Me)	Modal value (Mo)	Coefficient of asymmetry (As)
Abundance of blue-greens (specimens $\text{dm}^{-3}$ )	226	17217	21624	125.60	10237	26191	-0.41
Water temperature ( $^{\circ}\text{C}$ )	226	18.3	4.7	25.68	19.2	14.1	+0.89
Orthophosphate concentration ( $\text{mgPO}_4\text{dm}^{-3}$ )	226	0.33	0.53	160.61	0.16	0.01	+0.60

### Changes in the numbers of blue-green algae in the annual cycle in the 1998-2003 period as related to water temperature and orthophosphate concentration

Changes in the numbers of blue-green algae in the annual cycle in shallow eutrophic lakes, such as Lake Jeziorak Mały, may be affected by a variety of factors, including sunlight penetration, water temperature changes, mixing, and biogenic resuspension (phosphorus) of sediments (Sommer *et al.* 1986 as cited in Findenegg 1943). Changes in the abundance of blue-greens in Lake Jeziorak Mały were analyzed with respect to changes in water temperature (Fig. 1) and orthophosphate concentration (Fig. 2).

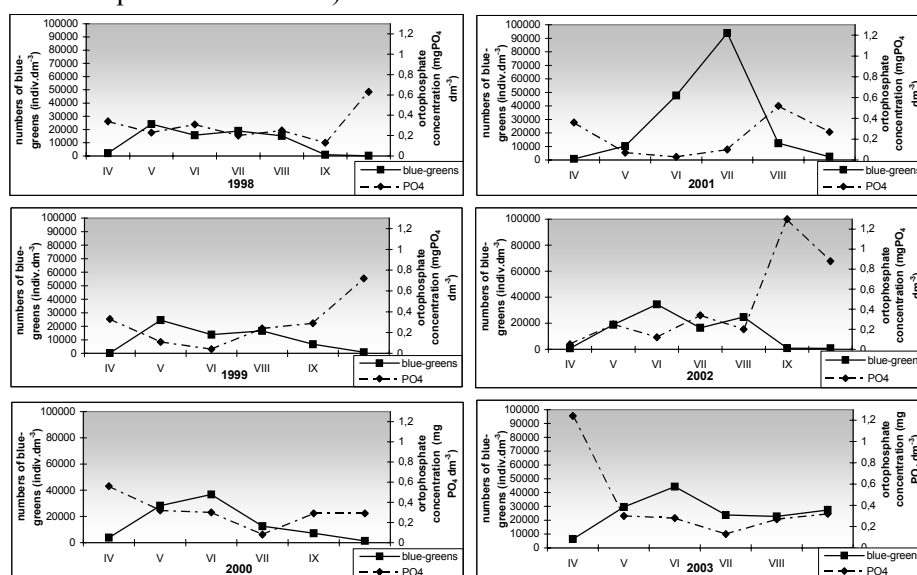


**Fig. 1.** Changes in the numbers of blue-green algae in the annual cycle as related to water temperature in Lake Jeziorak Mały.

Figure 1 shows that an increase in water temperature above 13°C was followed by an increase in the densities of blue-greens in the annual cycle. Their maximum abundance was recorded in a temperature range of 17 to 23.9°C (Zębek 1998, 2005). Their biomass declined along with a decrease in water temperature below 20°C, which results from the natural life cycle of these prokaryotic algae.

Differences in the population density of blue-green algae were observed in the 1998-2003 period. Two abundance peaks were recorded in the summers of

1998, 1999, and 2002 (in May and July, in May and August, and in June and August, respectively), and one in the summers of 2000, 2001, and 2003 (in June and July). The lowest abundance of blue-greens was recorded in 1998 (16628 specimens  $\text{dm}^{-3}$  in July), and the highest in 2001 (93830 specimens  $\text{dm}^{-3}$  at a water temperature of 23.7°C).



**Fig. 2.** Changes in the numbers of blue-green algae in the annual cycle as related to orthophosphate concentration in Lake Jeziorak Maly.

Numerous authors demonstrated that the development of blue-green algae, especially in spring, is affected by water temperature and orthophosphate concentration (Vollenweider 1968, Bucka 1989, Mayer *et al.* 1997, Huszar and Caraco 1998). Sommer *et al.* (1986) found that an increase in water temperature, even from 13 to 17°C, is followed by an increase in the numbers of these prokaryotic algae. The domination of blue-greens in shallow eutrophic and hypertrophic lakes, primarily in late spring and in summer, was also reported by other authors. Spodniewska (1986) observed higher densities of blue-green algae in spring in shallow pond-type eutrophic lakes, and Nixdorf (1985, 1994) noted the maximum biomass of these prokaryotic algae in May and July. The data above and the literature cited indicate that increased water temperature is conducive to the growth of blue-greens, which are present in the greatest numbers at the maximum value of this parameter (23.7°C).

Another parameter analyzed in the study was the orthophosphate content of the water. In the majority of lakes phosphorus is considered a decisive factor in

the production of phytoplankton, including blue-green algae (Edmondson 1991 as cited in Krebs 1996). In experiments on pond-type lake fertilization with phosphorus, algae would sometimes show symptoms of the deficiency of other nutrient elements, such as nitrogen and carbon. However, this situation would change over time as a consequence of certain long-term processes (Schindler 1977 as cited in Krebs 1996). Physical factors, such as water motion and gas exchange, regulate CO<sub>2</sub> availability, so carbon dioxide seldom prevents algal growth. Nitrogen fixation by blue-greens is also possible. The species that benefit from nitrogen deficiency make this element readily available to algae, and the lake may be restored to the original state when the limiting factor is phosphorus. Ultimately, it was found that plankton biomass was significantly correlated with the total phosphorus concentration in the water (Krebs 1996).

In Lake Jeziorak Mały orthophosphate concentration ranged from 0.03 mg PO<sub>4</sub> dm<sup>-3</sup> in June 2001 to 1.30 mg PO<sub>4</sub> dm<sup>-3</sup> in September 2002. Figure 2 shows a relationship between the occurrence of blue-green algae and orthophosphate level in the annual cycle. In spring, when the amounts of this biogenic element were large (0.33 mgPO<sub>4</sub> dm<sup>-3</sup> in 1999 to 1.24 mgPO<sub>4</sub> dm<sup>-3</sup> in 2003), the abundance of blue-greens was very low (298 to 6325 specimens dm<sup>-3</sup>). In summer an increase in the biomass of these prokaryotic algae was accompanied by a decline in orthophosphate concentration. The maximum abundance of blue-greens was recorded at an orthophosphate level of 0.10 to 0.30 mg PO<sub>4</sub> dm<sup>-3</sup>. The minimum population density of blue-greens was observed in fall 2002, when the concentration of this biogenic element in the water reached 1.30 mgPO<sub>4</sub> dm<sup>-3</sup>.

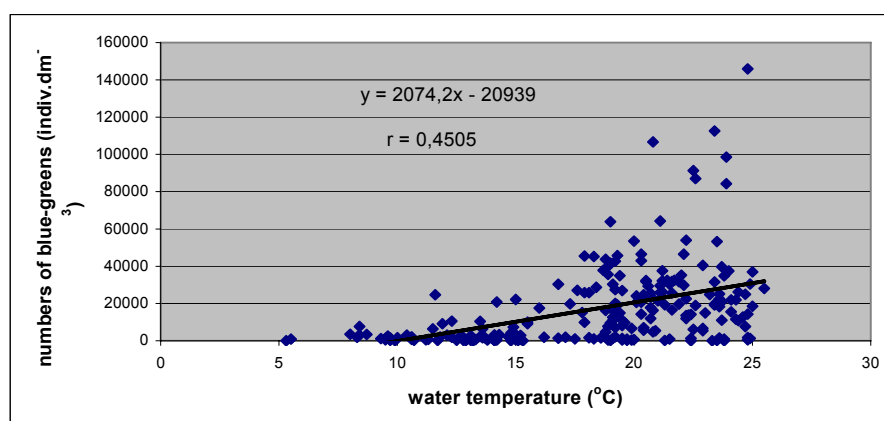
Trojan (1980) pointed out that planktonic algae, including the blue-greens, require nutrients (especially phosphorus) to grow and reproduce. Wernicke and Nicklish (1986) reported a higher phosphorus uptake rate by the blue-greens at low water temperatures. This phenomenon is observed primarily in spring, when at 5°C the available phosphorus is present in great abundance in the water. This element becomes a factor limiting algal development only at 20°C. Noges and Laugaste (1998) observed the maximum concentrations of orthophosphates in March (1 mg PO<sub>4</sub>dm<sup>-3</sup>) and October (0.65mg dm<sup>-3</sup>) in a shallow eutrophic lake; the blue-greens formed the predominant algal group in this water body in summer (August) when the level of this nutrient was low (0.02 mgPO<sub>4</sub> dm<sup>-3</sup>).

During summer in Lake Jeziorak Mały, when water temperatures were high, the maximum abundance of blue-green algae was accompanied by a decrease in orthophosphate content to 0.01 mg PO<sub>4</sub> dm<sup>-3</sup>. This may suggest that in summer the blue-greens contributed to reducing the phosphorus content of the water. However, the decline in the amount of this biogenic element over the year could also be caused by other planktonic algae or by other factors. According to

Reynolds (1980), the annual succession patterns of phytoplankton, including the blue-greens, may also be affected by biological interactions between organisms, such as competition for food. In late summer and early fall phosphorus uptake by large diatoms and filamentous green algae is also possible. For instance, diatoms compete for phosphorus when there is a high Si:P ratio (Ferguson *et al.* 1982). In Lake Jeziorak Mały in fall 2001 and 2002, the decrease in orthophosphate concentration continued even when the abundance of blue-green algae was low. This could be a consequence of phosphorus uptake by other planktonic algae, such as diatoms, or phosphorus release from sediments as a result of water circulation.

### Factors affecting changes in the abundance of blue-green algae in the annual cycle

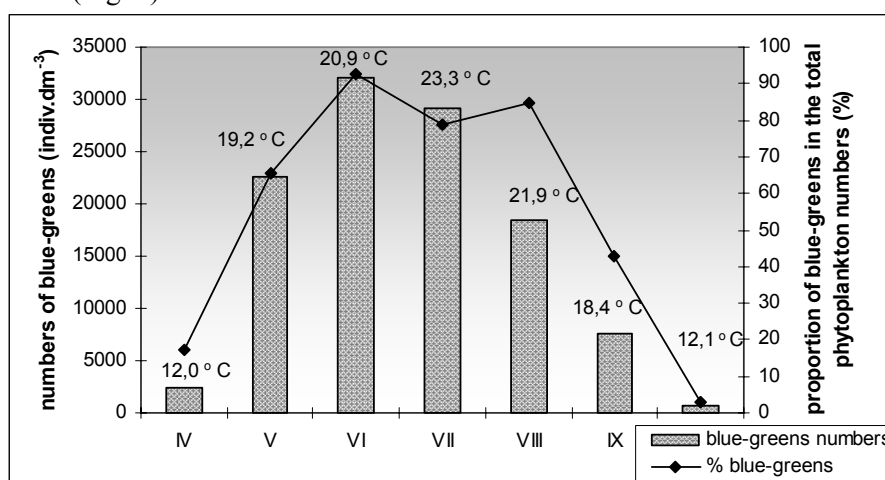
Changes in the numbers of blue-greens observed over the annual cycle in Lake Jeziorak Mały could have been determined by previously mentioned factors. The analysis above indicates that both water temperature and orthophosphate concentration could have had an impact on the abundance of blue-greens. The opposite is also possible; the population size of these algae could have affected the orthophosphate content of the water.



**Fig. 3.** Relationships between water temperature and the abundance of blue-green algae in the littoral zone of Lake Jeziorak Mały in the 1998-2003 period.

Figure 3 shows that an increase in water temperature by 1°C was followed by an increase in the abundance of blue-greens by 2074 specimens dm<sup>-3</sup>, and that this correlation was statistically significant ( $r = 0.4505$ ). As for

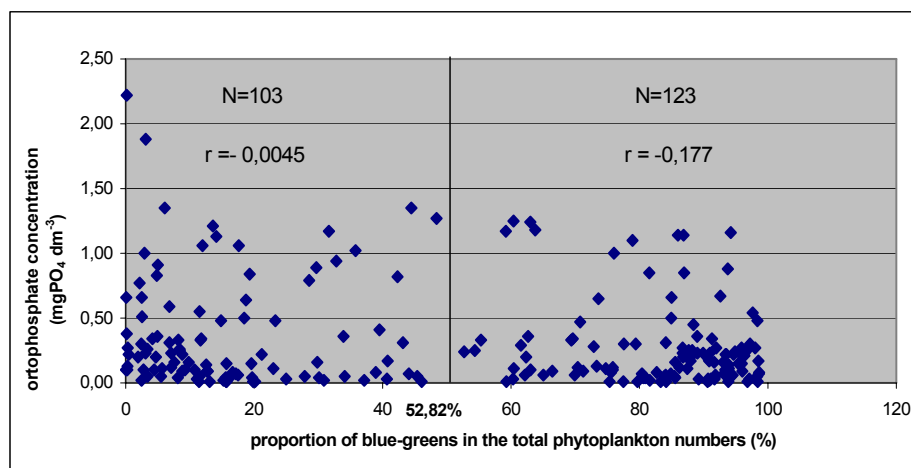
orthophosphate concentration, the coefficient of correlation was negative and statistically non-significant ( $r = -0.1600$ ). Was this situation the same throughout the year? It is a well-known fact that blue-green algae have their peak of development in summer. In Lake Jeziorak Mały the blue-greens were present in greatest numbers (over 50% of the total phytoplankton numbers) from May to August when the water temperature range was from 19.2°C to 21.9°C (Fig. 4).



**Fig. 4.** Abundance and proportion of blue-green algae in the total phytoplankton numbers as related to water temperature in the annual cycle in Lake Jeziorak Mały (means for the years from 1998 to 2003).

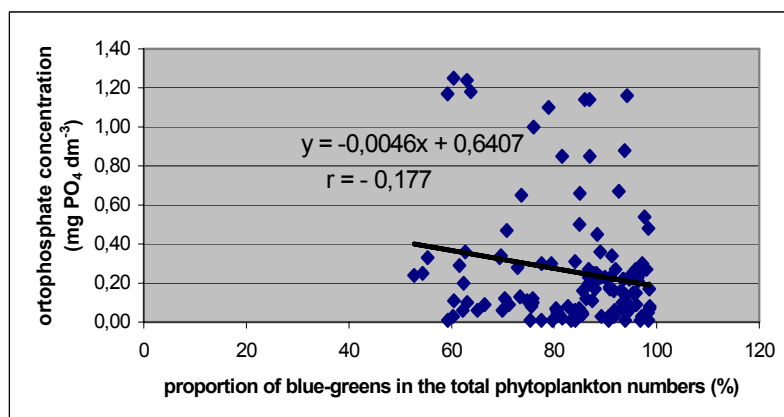
Due to this, two data sets were selected for further analysis. The selection criterion was the average proportion of blue-greens in the total phytoplankton biomass, adopted at a level of 52.82%. The abundance of blue-greens was below this value in April, September, and October, and above it from May to August. Spodniewska (1986) observed biomass peaks of blue-green algae in Lake Hawskie in summer. Their proportion of the total phytoplankton biomass exceeded 30% and reached as much as 90% during water blooms.

Figure 5 shows that in April, September, and October (spring and fall) there was a statistically significant correlation between the numbers of blue-green algae and orthophosphate concentration ( $r = -0.0045$ ). In the period from May to August, when the blue-greens accounted for more than 52.82% of phytoplankton numbers, the coefficient of correlation was  $r = -0.177$ , and was statistically significant at a level of 5% for the number of measurements  $N=123$ .



**Fig. 5.** Relationships between the proportion of blue-green algae in the total phytoplankton numbers and orthophosphate concentration in Lake Jeziorak Mały in the 1998-2003 period (52.82% - mean proportion of blue-greens in the total phytoplankton numbers).

The straight line regression equation in Figure 6 shows that an increase in the numbers of blue-greens by 1% reduced orthophosphate concentration by 0.0046 mg PO<sub>4</sub> dm<sup>-3</sup>.



**Fig. 6.** Relationships between the proportion of blue-green algae in the total phytoplankton numbers above 52.82% and the orthophosphate concentration in Lake Jeziorak Mały in the 1998-2003 period.

The analysis of the relationships between the variables suggests that the key factor influencing phytoplankton development in the annual cycle was water temperature, which was confirmed by the high value of the correlation coefficient. No statistically significant correlation was found between orthophosphate concentration and the occurrence of blue-green algae, which may be a consequence of the ready availability (*ad libitum*) of this element, especially at low water temperatures. Under conditions when the blue-green algae dominated (over 52.82% of the total phytoplankton numbers) and water temperatures were high, this correlation was statistically significant. This indicates that in the period from May to August the blue-greens could contribute to reducing the orthophosphate concentration in the water. However, the amounts of this biogenic element in the water could also have been related to other factors, such as low water temperature in spring and its ready availability to plant organisms, water circulation in fall resulting in its release from sediments, or, finally, phosphorus uptake by other algal groups, such as diatoms.

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