# Nutrient and Chl. *a* distributions in surface waters of Lake Baikal before and after the thermal stratification development

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**Abstract**

Soluble reactive phosphorus (SRP), ammonia, nitrite+nitrate and Chl. *a* were measured in 24 surface waters from southern Lake Baikal in June 2002, while those in 17 surface water samples from southern and partly central Lake Baikal were determined in August of the same year. Water temperatures indicated that these two months were before and after the thermal stratification development, respectively.

SRP and nitrite+nitrate decreased significantly and Chl. *a*, dominated by the <10 $\mu$m fraction, increased 3-fold from June to August, while a similar low level of ammonia was recorded in these two months. Averages and standard deviations in June were 0.18±0.04 $\mu$mol $l^{-1}$ for SRP, 0.2±0.1 $\mu$mol $l^{-1}$ for ammonia, 3.3±0.7 $\mu$mol $l^{-1}$ for nitrite+nitrate and 0.6±0.1 $\mu$g $l^{-1}$ for Chl. *a*. Those in August were trace for SRP, 0.3±0.1 $\mu$mol $l^{-1}$ for ammonia, 0.4±0.1 $\mu$mol $l^{-1}$ for nitrite+nitrate and 1.7±0.5 $\mu$g $l^{-1}$ for Chl. *a*. These results suggest that SRP and nitrite+nitrate were supplied to the surface from deeper waters by seasonal mixing and taken up by phytoplankton during the development of thermal stratification. On the other hand, the distribution of ammonia in the surface water was independent from water movements, suggesting that the ammonia uptake and regeneration was in equilibrium at such a low concentrations throughout the year.

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## Introduction

The water chemistry of Lake Baikal has long been studied by Russian scientists. A summary of their earlier studies was given in a monograph by Kozhov (1963), however, modern information on nutrients in Lake Baikal is limited. Nagata et al. (1994) presented three vertical profiles for soluble reactive phosphorus (SRP) and nitrite+nitrate in southern Lake Baikal in late July 1992. SRP and nitrite+nitrate were almost absent in the surface layer, increasing with depth up to 0.4 $\mu$mol $l^{-1}$ for SRP and 8 $\mu$mol $l^{-1}$ for nitrite+nitrate at 50 m. Goldman et al. (1996) showed 11 vertical sections down to 250 m for SRP and nitrate from the southern end to the northern end of Lake Baikal in July 1990. The south basin was thermally stratified but the north basin was not, resulting in a dramatic difference in nutrient distribution from south to north: depletion of nutrients from the surface layer in the south, while vertically uniform and rich in the north. Watanabe and Drucker (1999) recorded phosphate and nitrite+nitrate from the surface to 50 m at a pelagic station in the southern basin of Lake Baikal in late July 1992, showing that both nutrients were almost absent from the surface. SRP increased with depth to about 0.3 $\mu$mol $l^{-1}$ at 50 m and nitrite+nitrate to 7 $\mu$ mol $l^{-1}$. Data on vertical profiles for SRP and nitrate in southern Lake Baikal in March, August and October 1999 are available in Yoshida et al. (2003). From their profiles, SRP in the surface layer ranged from almost zero in August and October to 0.2 $\mu$mol $l^{-1}$ in March. SRP increased to about 0.3 $\mu$ mol $l^{-1}$ below 50-100 m in all months. Nitrate in the surface layer varied from almost 0 $\mu$mol $l^{-1}$ in August to 5 $\mu$mol $l^{-1}$ in March. It increased to 5-6 $\mu$mol $l^{-1}$ below 100 m in all months. Average concentrations, 0.24±0.06 $\mu$mol $l^{-1}$ for ammonia, 0.04±0.02 $\mu$mol $l^{-1}$ for nitrite, 0.34±0.08 $\mu$mol $l^{-1}$ for nitrate and 0.02±0.01 $\mu$mol $l^{-1}$ for dissolved inorganic phosphorus, in 15 surface water samples from southern and partly central Lake Baikal in August 2002 are given in Kihira et al. (2008).

As shown above, some vertical profiles of SRP and nitrate in Lake Baikal are available. However, information on ammonia in the lake is extremely limited. Furthermore, data on the basin wide horizontal distribution of nutrients is unavailable except for the 11 vertical sections by Goldman et al (1996) and the average concentrations in Kihira et al. (2008). The present results provide changes in the horizontal distributions of SRP, ammonia, nitrite+nitrate and Chl. *a* in southern and partly central Lake Baikal in 2002, before and after thermal stratification development.

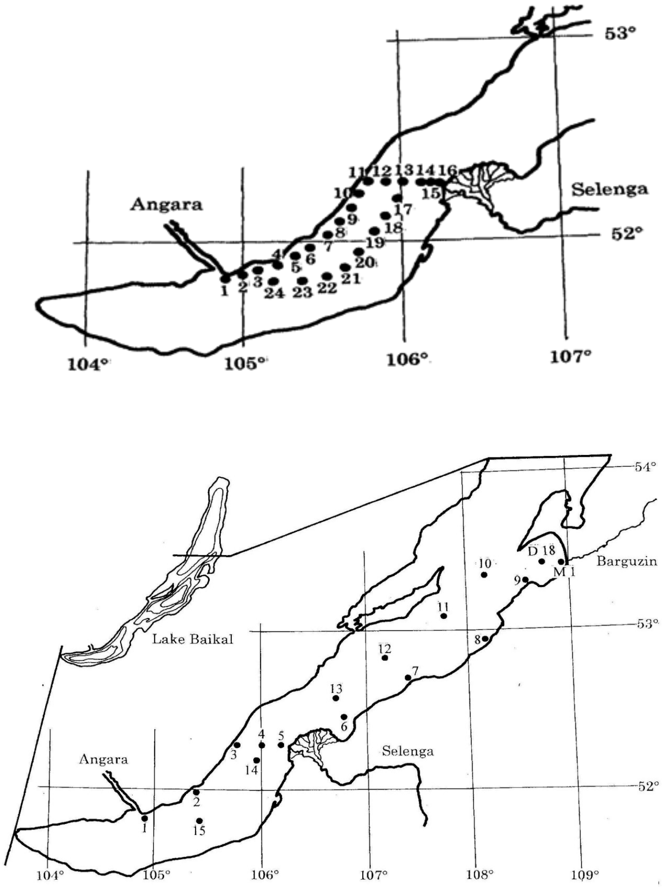


Fig. 1. Station locations in Lake Baikal in June (upper) and August (lower) 2002

## Materials and methods

Twenty-four bucket surface water samples were collected from southern Lake Baikal by scientists on board the RV *Obruchev* of the Limnological Institute SB RAS from 28 to 30 June 2002 (Fig. 1 upper). Similarly 17 samples from southern and part of the central Lake Baikal were collected by scientists on board the RV *Vereshagin* of the above institute from 24 to 31 August in the same year (Fig. 1 lower). Water samples were immediately filtered through pre-ignited Whatman GF/F glass fiber filters (nominal porosity, 0.7 $\mu$m). The filters and filtrates were frozen on board ship in order to carry out the chemical analyses in Japan. Chl. *a* was determined by fluorometry (Model 10-AU, Turner Designs, USA). Only a single analysis of Chl. *a* was made at each station in June except for Stn. 24:
to evaluate the precision of the Chl. *a* analysis a four replicate analysis was

conducted at Stn. 24. In addition, the size-fractionation of Chl. *a* was carried out by passing the water sample through a 10 μm nylon net at this station.

Chl. *a* was size-fractionated in August by filtering the water samples through a 10 μm nylon net and then a 2 μm Nuclepore filter. Chl. *a* in each fraction was analyzed in duplicate. Nitrite+nitrate was determined by the cadmium reduction method [Strickland and Parsons 1972], ammonia by the phenol hypochlorite method [Solõrzano 1969] and soluble reactive phosphorus (SRP) by the molybdate blue method [Strickland and Parsons 1972]. Nutrient analyses were conducted in duplicate. Water temperature was measured by a mercury thermometer in June and a thermistor thermometer in August. Transparency was measured by a Secchi Disc.

## Results

### June

Surface water temperatures at Stn. 1 to Stn. 10 ranged from 5.1 ℃ to 8.0 ℃ (Table 1), however, the water temperatures at the other stations are unavailable because the thermometer was broken. Transparency varied from 0.5 m to 16 m, and when the turbid river mouth stations of the River Selenga (Stns. 14, 15 and 16) were excluded the average and standard deviation of the transparency was 12.9±2.1 m.

SRP ranged from 0.10 μmol $l^{-1}$ (Stns. 14 and 15 in Table 1) to 0.24 μmol $l^{-1}$ (Stn. 22), with the average of 0.18±0.04 μmol $l^{-1}$ (Table 2). The former stations were located near the mouth of River Selenga and the latter located in pelagic Baikal. Ammonia ranged from 0.1 μmol $l^{-1}$ to 0.3 μmol $l^{-1}$ with an average of 0.2±0.1 μmol $l^{-1}$. Nitrite+nitrate was rich when compared with ammonia, and ranged from 2.2 μmol $l^{-1}$ to 5.1 μmol $l^{-1}$ with an average of 3.3±0.7 μmol $l^{-1}$.

The concentrations of Chl. *a* in the surface waters ranged from 0.5 to 0.9 μg $l^{-1}$ with an average of 0.6±0.1 μg $l^{-1}$ except near the River Selenga (Stns. 14, 15 and 16). The highest concentration, 25.7 μg $l^{-1}$, was recorded at Stn. 16, the station closest to the River Selenga. Though Chl. *a* dropped markedly to about 1.5 μg $l^{-1}$ from Stn. 16 to Stns. 14 and 15, the concentrations were still high compared with those of the other stations. The average and standard deviation for the four replicate analyses of Chl. *a* at Stn. 24 was calculated to be 0.6±0.0 μmol $l^{-1}$, showing good precision of the analytical procedure. Chl. *a* in the <10 μm fraction at this station was 0.5±0.0 μmol $l^{-1}$, and thus represented 83% of the total.

### August

The surface water temperatures at Stn. 1 to Stn. 9 were about 17 ℃ and were significantly higher than those at Stn. 10 to Stn. 15, which ranged from 13 to 15 ℃

Table 1. Water temperature (WT) and transparency (Tr ), and concentrations of soluble reactive phosphorus (SRP), ammonia, nitrite+nitrate (NOx) and Chl. *a* in surface waters of southern Lake Baikal in late June 2002

| Stn | Date | WT (ºC) | Tr (m) | SRP ($\mu$mol l$^{-1}$) | Ammonia ($\mu$mol l$^{-1}$) | NOx ($\mu$mol l$^{-1}$) | Chl. *a* ($\mu$g l$^{-1}$) |
|---|---|---|---|---|---|---|---|
| 1 | June 28 | 6.5 | 16 | 0.22 | 0.3 | 4.4 | 0.5 |
| 2 | 28 | 6.0 | 15 | 0.20 | 0.2 | 4.7 | 0.7 |
| 3 | 28 | 6.5 | 14 | 0.21 | 0.2 | 2.2 | 0.8 |
| 4 | 28 | 5.5 | 12 | 0.23 | 0.2 | 2.5 | 0.7 |
| 5 | 28 | 6.5 | 12 | 0.20 | 0.1 | 2.7 | 0.9 |
| 6 | 28 | 7.0 | 9 | 0.16 | 0.2 | 3.0 | 0.7 |
| 7 | 28 | 6.0 | 14 | 0.20 | 0.2 | 5.1 | 0.6 |
| 8 | 28 | 5.1 | 15 | 0.21 | 0.3 | 4.1 | 0.6 |
| 9 | 28 | 8.0 | 12 | 0.14 | 0.1 | 3.9 | 0.5 |
| 10 | 28 | 6.3 | 14 | 0.20 | 0.2 | 2.9 | 0.6 |
| 11 | 29 | - | 16 | 0.22 | 0.2 | 3.1 | 0.5 |
| 12 | 29 | - | 13 | 0.16 | 0.1 | 3.0 | 0.9 |
| 13 | 29 | - | 12 | 0.13 | 0.2 | 3.5 | 0.8 |
| 14 | 29 | - | 7 | 0.10 | 0.2 | 3.4 | 1.4 |
| 15 | 29 | - | 4 | 0.10 | 0.2 | 3.1 | 1.5 |
| 16 | 29 | - | 0.5 | 0.23 | 0.1 | 2.6 | 25.7 |
| 17 | 30 | - | 10 | 0.12 | 0.2 | 2.4 | 0.6 |
| 18 | 30 | - | 11 | 0.13 | 0.1 | 3.0 | 0.7 |
| 19 | 30 | - | 12 | 0.14 | 0.2 | 3.3 | 0.6 |
| 20 | 30 | - | 10 | 0.18 | 0.2 | 3.4 | 0.6 |
| 21 | 30 | - | 13 | 0.17 | 0.2 | 3.3 | 0.5 |
| 22 | 30 | - | 16 | 0.24 | 0.1 | 3.4 | 0.5 |
| 23 | 30 | - | 11 | 0.21 | 0.2 | 2.8 | 0.6 |
| 24 | 30 | - | 13 | 0.22 | 0.1 | 3.0 | 0.6 |

(Table 3). The former stations were located mainly near the coast and the latter in the central area of the lake (Fig. 1 lower). Three vertical profiles of water temperature are available in August, which indicate clear thermal stratification (Fig. 2). Transparency varied from 2 to 7 m, and when the datum from the turbid river mouth station of the River Barguzin, Stn. M1, was excluded the average transparency was 6.2±1.0 m.

With a few exceptions, the concentrations of SRP in the surface waters were at or below the lower limit of determination, i. e. $\leq 0.05$ $\mu$mol l$^{-1}$ (Table 3). The

Table 2. Averages and standard deviations of nutrient and Chl. *a* concentrations in June and August 2002

| | Tr | SRP | Ammonia | NOx | Chl. *a* |
|---|---|---|---|---|---|
| | (m) | ($\mu$mol $l^{-1}$) | ($\mu$mol $l^{-1}$) | ($\mu$mol $l^{-1}$) | ($\mu$g $l^{-1}$) |
| June | 12.9±2.0[a] | 0.18±0.04 | 0.2±0.1 | 3.3±0.7 | 0.6±0.1* |
| August | 6.2±1.0[a] | ≤0.05 | 0.3±0.1 | 0.4±0.1 | 1.7±0.5* |

* Excluding Stns. 14, 15, 16 in June and Stn. M1 in August, which are located near river mouths

highest concentration of SRP, 0.20 $\mu$mol $l^{-1}$, was recorded at Stn. M1. The concentrations of ammonia ranged from 0.2 to 0.4 $\mu$mol $l^{-1}$ with an average of 0.3±0.1 $\mu$mol $l^{-1}$. Those of nitrite+nitrate ranged from 0.3 to 0.7 $\mu$mol $l^{-1}$ with an average of 0.4±0.1 $\mu$mol $l^{-1}$.

The concentrations of Chl. *a* ranged from 0.7 $\mu$g $l^{-1}$ at Stn. D18 to 3.0 $\mu$g $l^{-1}$ at Stn. 15, except at Stn. M1 where the Chl. *a* concentration was 5.8 $\mu$g $l^{-1}$.
The average was calculated to be 1.7±0.5 $\mu$g $l^{-1}$, except at Stn. M1. The Chl. *a* in the >10 $\mu$m fraction ranged from 7 to 37% (Table 3), with an average of 21±14%. The Chl. *a* in the 2-10 $\mu$m fraction ranged from 17 to 50%, with an average of 35±10%. The Chl. *a* in the >2 $\mu$m fraction ranged from 32 to 69%, with an average of 44±10%.

## Discussion

According to Kozhov (1963), southern Lake Baikal is covered with ice from mid January to early May. Seasonal water mixing in Lake Baikal is limited to the upper 250-300 m. The water temperature in this layer increases very slowly after ice melt, because of the thick mixing layer. The vernal homothermy lasts 2 to 3 weeks and starts in mid June in the south basin and in mid July in the northern part. Based on Kozhov (1963) and the surface water temperatures of around 6 ℃ in this study (Table 1), the field observations in June seemed to be conducted during the final stage of the homothermy or extremely early stage of the thermal stratification onset. Thus the results of June and August are thought to be examples of a period before and after the thermal stratification development, respectively.

SRP, nitrite+nitrate and transparency decreased significantly from June to August. SRP decreased to a level around the limit of determination, nitrite+nitrate to 1/8 and transparency to 1/2 (Table 2). On the other hand, Chl. *a* increased 3-fold in the same period. A similar low level of ammonia was recorded in these two months. SRP and nitrite+nitrate have higher concentrations in deeper waters [Nagata et al. 1994; Goldman et al. 1996; Watanabe and Drucker 1999; Yoshida et

Table 3. Water temperature (WT) and transparency (Tr), and concentrations of soluble reactive phosphorus (SRP), ammonia, nitrite+nitrate (NOx) and Chl. *a* (figures in the parentheses are percentages of the totals) in surface waters of southern and partly central Lake Baikal in late August 2002 (nutrients at Stns. 4, 10, D18 and M1 are from Satoh et al. 2006)

| Stn | Date | WT | Tr | SRP | Ammonia | NOx | Chl. *a* ($\mu$g l$^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | (ºC) | (m) | ($\mu$mol l$^{-1}$) | ($\mu$mol l$^{-1}$) | ($\mu$mol l$^{-1}$) | >10 $\mu$m | 10-2 $\mu$m | <2 $\mu$m |
| 1 | Aug. 24 | 17.1 | 6 | ≤ 0.05 | 0.4 | 0.5 | 0.4 (25) | 0.5 (31) | 0.7 (44) |
| 2 | 24 | 16.4 | 6 | ≤ 0.05 | 0.2 | 0.4 | 0.4 (22) | 0.7 (39) | 0.7 (39) |
| 3 | 24 | 16.9 | 6 | ≤ 0.05 | 0.4 | 0.6 | 0.3 (20) | 0.6 (40) | 0.6 (40) |
| 4 | 24 | 16.7 | 6 | ≤ 0.05 | 0.2 | 0.3 | 0.5 (33) | 0.3 (20) | 0.7 (47) |
| 5 | 24 | 17.2 | 4 | ≤ 0.05 | 0.2 | 0.3 | 0.6 (30) | 0.8 (40) | 0.6 (30) |
| 6 | 24 | 17.7 | - | ≤ 0.05 | 0.3 | 0.3 | 0.1 ( 7) | 0.7 (50) | 0.6 (43) |
| 7 | 25 | 16.3 | 7 | ≤ 0.05 | 0.2 | 0.3 | 0.1 ( 7) | 0.7 (50) | 0.6 (43) |
| 8 | 25 | 17.4 | 5 | ≤ 0.05 | 0.3 | 0.4 | 0.6 (32) | 0.7 (36) | 0.6 (32) |
| 9 | 25 | 17.5 | 7 | ≤ 0.05 | 0.3 | 0.4 | 0.4 (31) | 0.4 (31) | 0.5 (38) |
| 10 | 29 | 12.9 | 6 | 0.07 | 0.4 | 0.4 | 1.6* | - | - |
| 11 | 31 | 13.1 | 8 | ≤ 0.05 | 0.4 | 0.7 | 0.2 (13) | 0.5 (34) | 0.8 (53) |
| 12 | 31 | 14.8 | 7 | ≤ 0.05 | 0.2 | 0.3 | 0.0 ( 0) | 0.7 (50) | 0.7 (50) |
| 13 | 31 | 14.3 | 7 | ≤ 0.05 | 0.2 | 0.3 | 0.1 ( 8) | 0.3 (23) | 0.9 (69) |
| 14 | 31 | 13.2 | 6 | ≤ 0.05 | 0.2 | 0.3 | 0.8 (35) | 0.4 (17) | 1.1 (48) |
| 15 | 31 | 11.8 | 6 | 0.10 | 0.2 | 0.6 | 1.1 (37) | 0.9 (30) | 1.0 (33) |
| D18 | 26 | 16.6 | 7 | ≤ 0.05 | 0.2 | 0.4 | 0.7* | - | - |
| M1 | 28 | 17.1 | 2 | 0.20 | 0.4 | 0.4 | 5.8* | - | - |

* Chl. *a* was not fractionated in these stations. Figures are total concentrations of Chl. *a*.

al. 2003]. Seasonal water mixing supplies these nutrients from the depths to the surface, resulting in high nutrient concentrations in the surface water in June. Seasonal water mixing also causes the phytoplankton to disperse throughout the mixed layer, resulting in lower Chl. *a* concentration and higher transparency in June as compared with those in August. On the other hand, phytoplankton quickly take up nutrients from the surface water and grow after the onset of thermal stratification [Goldman et al. 1996], resulting in higher Chl. *a* and lower nutrient concentrations and transparency in August.

However, the present results show that the behavior of ammonia in the surface water differs from those of SRP and nitrite+nitrate. The concentration of ammonia in the surface water was independent from water movement, suggesting that the ammonia uptake and regeneration is in equilibrium at such a low concentrations

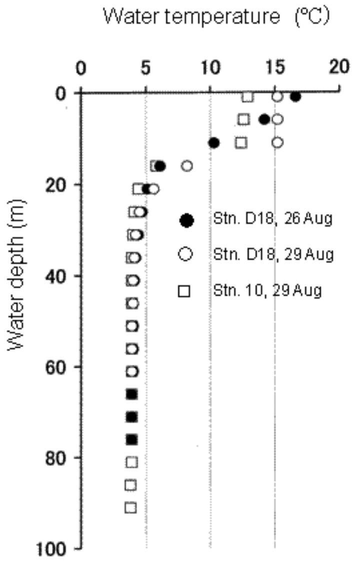


Fig. 2. Vertical distributions of water temperature at Stn D18 on 26 and 29 August, and Stn. 10 on 29 August

throughout the year. Goldman et al. (1996) showed that the ammonia uptake rate and regeneration rate in Lake Baikal were approximately in equilibrium. The present results indicate that not only in the stratified condition but also in the homothermic condition, ammonia is in equilibrium between uptake and regeneration. Since ammonia is the preferred nitrogen source of phytoplankton [Syrett and Morris 1963; Conway 1977; McCarthy et al. 1977], regenerated ammonia in the surface water will be immediately taken up by phytoplankton before it is subjected to nitrification.

Kihira et al. (2008) independently determined nutrients including ammonia in aliquots of the same water samples in August of the present study. They give averages: 0.24±0.06 $\mu$mol $l^{-1}$ for ammonia, 0.04±0.02 $\mu$mol $l^{-1}$ for nitrite, 0.34±0.08 $\mu$mol $l^{-1}$ for nitrate and 0.02±0.01 $\mu$mol $l^{-1}$ for DIP. The present results are in accord with those of Kihira et al. (2008). Ammonia concentrations were not reported in the earlier studies of Nagata et al. (1994), Goldman et al. (1996), Watanabe and Drucker (1999) and Yoshida et al. (2003). Probably one of the reasons why they did not determine ammonia is that ammonia is easily contaminated during sample storage prior to chemical analysis. We did not pay special attention to the sample storage of ammonia: they were treated in same way as those for SRP and nitrite+nitrate. Whether or not the ammonia samples of the present study were contaminated is difficult to prove. However, contamination would result in sporadic high concentrations of ammonia. There were no such sporadic high concentrations in the present results, strongly suggesting that the present samples were not contaminated.

The surface water temperatures were lower at the central stations than at the coastal stations in August (Table 3). However, the difference is not necessarily attributable to local differences between the coastal and the central stations. Vertical distributions of water temperature were measured at Stn. 10 on 29 August and at Stn. D18 twice on 26 and 29 August (Fig. 2). Though an epilimnion was unclear at Stn. D18 on 26 August, clear epilimnia from the surface to 10 m were found at Stns. 10 and D18 on 29 August. In between these two days, there was an extremely strong windy storm. The difference in the vertical thermal structures between the 26 and 29 August at Stn. D18 clearly demonstrates water mixing between warmer surface water and colder underlying water caused by the storm, resulting in a decrease in surface water temperature. The colder water temperatures from Stn. 10 to Stn. 15, which were observed after the storm, suggest the widespread influence of the storm (Table 3).

Transparency at Stn. 16 in June (Fig. 1, upper), the station closest to the River Selenga, was extremely low, 0.5 m (Table 1), as the water was muddy. Though the light conditions seemed unfavorable for phytoplankton photosynthesis, Chl. *a* concentration was extremely high (25.7 $\mu$g $l^{-1}$). Nutrients at this station were at the same levels as those of the other stations. Probably nutrients supplied from the River Selenga had been taken up by phytoplankton already, and resulted in stimulated growth of phytoplankton as indicated by the high Chl. *a*. The influence of river water also was observed at Stn. M1 in August, which was located in the mouth of the River Barguzin (Fig. 1, lower). Chl. *a* concentrations at this station was about 4-fold higher than those of the other stations (Table 3). However, in contrast to the results of SRP from stations near the River Selenga, SRP at Stn. M1 was the highest among the results in August. Satoh et al. (2006) showed that nitrogen was a limiting nutrient of the primary production at Stn. M1 though phosphorus was the limiting nutrient at Stns. 4, 10 and D18. The nitrogen limitation at this station may explain the relatively high concentrations of SRP.

The dominance of smaller phytoplankton is characteristic of Lake Baikal [Votintsev et al. 1972; Back et al. 1991; Nagata et al. 1994; Bondarenko et al. 1996;, Watanabe and Drucker 1999; Belykh and Sorokovikova 2003; Yoshida et al. 2003; Katano et al. 2005]. The present results agree with those of previous studies. Small phytoplankton <10 $\mu$m occupied 83% of the total at Stn. 24 in June. On average 79% of the Chl. *a* presented in the <10 $\mu$m fraction and that in the <2 $\mu$m fraction was 44% in August. Some microscopic results on the samples in August are given in Katano et al. [2005].

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## References

Back, R.C., D.W. Bolgrien, N.E. Guselnikova and N.A. Bondarenko (1991) Phytoplankton photosynthesis in southern Lake Baikal: Size-fractionated chlorophyll *a* and photosynthetic parameters. J. Great Lakes Res. 17:19-202.

Belykh, O.I. and E.G. Sorokovikova (2003) Autotrophic picoplankton in Lake Baikal: Abundance, dynamics, and distribution. Aquat. Ecosyst. Health. Manag. 6: 1-11.

Bondarenko, N.A., N.E. Guselnikova, N.F. Logacheva and G.V. Pomazkina (1996) Spatial distribution of phytoplankton in Lake Baikal, Spring 1991. Freshwater Biol. 35:517-523.

Conway, H.L. (1977) Interaction of inorganic nitrogen in the uptake and assimilation by marine phytoplankton. Mar. Biol. 39:221-232.

Goldman, C.R., J.J. Elser, R.C. Richards, J.E. Reuter, J.C. Priscu and A.L. Levin (1996) Thermal stratification, nutrient dynamics, and phytoplankton productivity during the onset of spring phytoplankton growth in Lake Baikal, Russia. Hydrobiologia 331:9-24.

Katano, T., S. Nakano, H. Ueno, O. Mitamura, K. Anbutsu, M. Kihira, Y. Satoh, V. Drucker and M. Sugiyama (2005) Abundance, growth and grazing loss rates of picophytoplankton in Barguzin Bay, Lake Baikal. Aquat. Ecol. 39: 431-438.

Kihira, K., K. Anbutsu, H. Azumi, M. Osamu, S. Nakano, T. Katnano, Y. Satoh, V. Drucker and M. Sugiyama (2008) Horizontal distribution and nutritional status of picophytoplankton in Lake Baikal in summer. Verh. Intern. Verein. Limnol. 30(4):593-602.

Kozhov, M. (1963) Lake Baikal And Its Life. Dr. Junk Publishers, The Hague.

McCarthy, J.J., W.R. Taylor and J.L. Taft (1977) Nitrogenous nutrition of the plankton in the Chesapeake Bay. 1. Nutrition availability and phytoplankton preference. Limnol. Oceanogr. 22:996-1011.

Nagata, T., K. Takai, K. Kawanobe, D-S. Kim, R. Nakazato, N. Guselnikova, N. Bondarenko, O. Mologawaya, T. Kostonova, V. Drucker, Y. Satoh and Y.

Watanabe (1994) Autotrophic picoplankton in southern Lake Baikal: Abundance, growth and grazing mortality during summer. J. Plankton Res. 16:945-959.

Satoh, Y., T. Katano, T. Satoh, O. Mitamura, K. Anbutsu, S. Nakano, H. Ueno, M. Kihira, V. Drucker, Y. Tanaka, T. Mimura, Y. Watanabe and M. Sugiyama (2006) Nutrient limitation of the primary production of phytoplankton in Lake Baikal. Limnology. 7:225-229.

Solõrzano, L. (1969) Determination of ammonia in natural waters by the phenol hypochlorite method. Limnol. Oceanogr. 14:799-801.

Strickland, J.D.H. and T.R. Parsons (1972) A practical Handbook of Seawater Analysis (2nd ed.). Bull. Fish. Res. Bd. Canada 167:1-310.

Syrett, P.J. and I. Morris (1963) The inhibition of nitrate assimilation by ammonia in *Chlorella*. Biochim. Biophys. Acta. 67:566-575.

Votintsev, K.K., A.I. Meshceryakova and G.I. Popovskaya (1972) The importance of ultrananoplanktonic algae in the primary production of Lake Baikal in the summer. Hydrobiol. J. 8:13-18.

Watanabe, Y. and V.V. Drucker (1999) Phytoplankton blooms in Lake Baikal, with reference to the lake's present state of eutrophication. In: Kawanabe, H., G.W. Coulter and A.C. Roosevelt (eds.), Ancient Lakes: Their Cultural and Biological Diversity. Kenobi Productions, Belgium, pp217-225.

Yoshida, Y., T. Sekino, M. Genkai-Kato, N.P. Logacheva, N.A. Bondarenko, Z. Kawabata, T.V. Khodzher, N.G. Melnik, S. Hino, K. Nozaki, Y. Nishimura, T. Nagata, M. Higashi and M. Nakanishi (2003) Seasonal dynamics of primary production in the pelagic zone of southern Lake Baikal. Limnology 4:53-62.