

Seasonal and vertical dynamics of nutrient and chlorophyll-a in the monomictic Lake Biwa

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Abstract. In the present study Shiga Prefecture's dataset on water quality of Lake Biwa, a monomictic lake was analyzed to detect vertical fluxes of nitrogen, phosphorus, and chlorophyll-a from time change rates in their concentration profiles. To compile and analyze historical water quality data, this study focused on seasonal and annual changes in nutrients and chlorophyll-a in Lake Biwa over a 35-year period. The study focused on monthly vertical flux profiles based on time changes in nitrogen, phosphorus, and chlorophyll-a, and it clarified the supply and removal dynamics in the lake with the production rate through nitrification and gross metabolic rate through assimilation and denitrification (nitrogen) or uptake, recycle, and sedimentation (phosphorus). Nutrients were well circulated in the total depth due to frequent destruction of stratification corresponding to a higher N:P ratio.

Key Words: biomass, chlorophyll-a, N:P ratio, nutrient's flux.

Introduction. Nutrient concentration in rivers is of particular importance to the ecology of rivers (Nikolaos et al 2022), and riverine transport of nutrients is also relevant to lake water (Ty et al 2022). Increasing nutrient loading to the aquatic eco-system results in enhanced primary production of phytoplankton (Al-Said et al 2019), leading to undesirable changes in aquatic resources such as degraded water quality, hypoxia, and harmful algal bloom, biodiversity loss, and affected food web structure (Wurtsbaugh et al 2019). Lake Biwa is the largest lake in Japan and provides great ecological and economic value (Kumagai 2008). However, over the past few decades, as with many lakes worldwide, Lake Biwa has undergone progressive eutrophication as a result of anthropogenic factors like agriculture activity, tourism, wastewater, and global warming (Hsieh et al 2010; Tsugeki et al 2010). Lake Biwa's phytoplankton biomass has decreased, and the dominant phytoplankton species has changed from net phytoplankton to nano-phytoplankton (Kishimoto et al 2013). Regardless, the primary productivity has increased in Lake Biwa due to the increase in picoplankton, which showed a low biomass, but a high productivity. Changes to the phytoplankton biomass (composition and size) and the fluctuation of nutrients have been recorded annually for decades. According to Nagata (1990), 50-90% of the primary production of phytoplankton was occupied by picoplankton. Kishimoto et al (2015) reported that the primary production in the north basin of Lake Biwa increased from 1980 to 2008, while chlorophyll-a (Chl-a) concentration exhibited an inverse trend. Cyanobacteria produce most of the lake's organic matter and largely determine the chemical oxygen demand (Ichise et al 2013). During the early summers of 1989 and 1990, the north basin of Lake Biwa was observed to have blooms of cyanobacteria such as *Synechococcus* spp. (Maeda et al 1992). Until now, nutritional status has been closely correlated with eutrophication and phytoplankton abundance. Total phosphorus (TP) and total nitrogen (TN) levels have been extensively used to assess the degree of eutrophication and to predict the productivity of all of the biological components of lakes and ponds (Peters 1986). Previous reports have attempted to diagnose the nutritional status mainly in the upper 20 m of Lake Biwa and

used this metric to represent changes to the lake's trophic status annually (Hsieh et al 2010, 2011; Kishimoto et al 2013). Only a few studies mentioned the seasonal supply rate or metabolic rate. Tsunogai et al (2018) estimated both the average nitrification rate and average assimilation rate of nitrate in the lake successfully, assuming that the metabolic rate of nitrate through denitrification was much less than in the highly oxic lake. Yoshimizu et al (2002) investigated the P nutrient budget in Lake Biwa and estimated that the inflow of P occupied 56% of TP metabolized in the lake's water column and re-mineralization took up only 44%. Tien et al (2020) reported that annual phosphate-phosphorus ($\text{PO}_4\text{-P}$) loading varied from 217 to 296 tons yr^{-1} in the North Basin and from 45 to 76 tons yr^{-1} in the South Basin. Furthermore, Tsunogai et al (2018) discovered that the majority of NO_3 metabolized in spring and summer was supplied by in situ nitrification within the epilimnion and upper thermocline. However, the methods to quantify nutrient dynamics are complicated and often can be inaccurate. The nutrients mass gradient estimation, which was an intriguing method of calculating the nutrients gradient fluctuation in the lake, could be correlated to the nutrients cycle (supply and use). Furthermore, the change of seasonal nutrient gradient could be linked with the succession of phytoplankton biomass and species in the seasonal and annual assessment through the flux profile of Chl-a.

This study investigates the long-term and seasonal changes in the physical and chemical water quality data in Lake Biwa over the past 35 years. To compile and analyze the seasonal dynamic of N, P, and phytoplankton (using Chl-a), the vertical nutrients flux profiles and their relevant gradient mass changes were evaluated.

Material and Method

Site description. Lake Biwa is in the center of the Honshu Islands in the Shiga Prefecture, northeast of Kyoto, Japan with an area of 674 km^2 and a maximum depth of 104 m. It contains two basins, a large north basin (616 km^2 , mean depth 45.5 m) and a small south basin (58 km^2 , mean depth 3.5 m) (Figure 1).

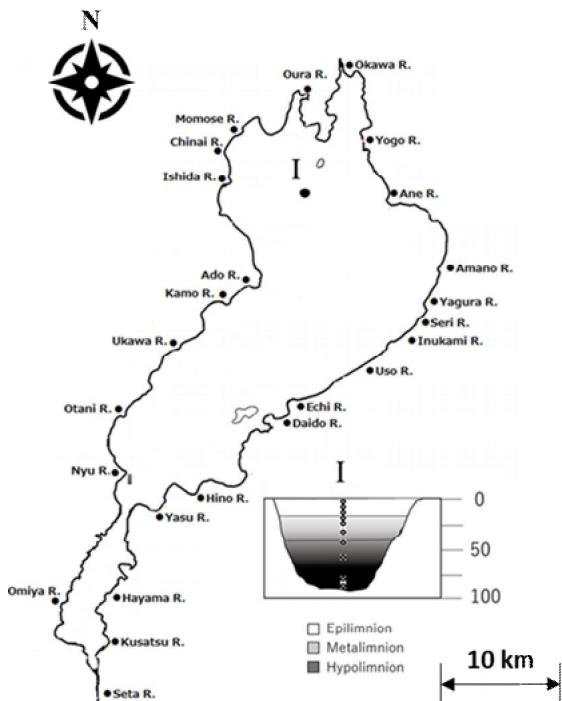


Figure 1. Map showing the sampling location at Imazuokichuo (I point) with layers of measurement in Lake Biwa. Filled circles along the coastline are river mouths.

The north basin is a warm monomictic lake with a circulation period from January to March, while the south basin is polymictic due to its shallowness (Tezuka 1992). The trophic status of the north basin was determined by Kishimoto et al (2013) as mesotrophic in terms of TN and oligotrophic in terms of TP.

Environmental analyses. The environmental data from 1980 to 2015 was used in this study. It included the concentration of TN, TP, Chl-a, silicate (SiO_2), pH, dissolved oxygen (DO), and temperature measures that were collected by Lake Biwa Environmental Research Institute (LBERI) at the station named Imazuokichuo ($35^{\circ}23'41''\text{N}$, $136^{\circ}07'57''\text{E}$). The samples were taken every other week during the day at depths of 0.5, 5, 10, 15, 20, 30, 40, 60, 80, and the bottom (88 m) in the north basin in Figure 1. The monthly average values of the layers were calculated. Furthermore, the 35 years of serial data were divided into five periods of seven years each (period I-V). Since Lake Biwa has a resident time of approximately 5.5 years, this can allow the data to be described in a reasonable manner and the changes in seasonality of all factors can be described more accurately. To visualize the water quality, we created contour plots for each of the three aforementioned factors. This method also enabled the following eutrophication trends in the north basin of Lake Biwa. In addition to nutrient concentration, TN, TP, and Chl-a fluxes were estimated to demonstrate the nutrient fluctuation according to vertical and seasonal changes. Although the changing rate of Chl-a is determined by both vertical transport and phytoplankton production on-site, the downcore distribution of Chl-a could be calculated using a random diffusive model (Boon & Duineveld 1998). The flux profiles $q_x(z)$ for $x = \text{TP}$, TN, and Chl-a were determined by

$$q_x(z) = \int_0^z \frac{\partial x}{\partial t} d\zeta \quad (1)$$

where: x is the monthly concentration of TP, TN, or Chl-a; t is time and ζ (m) is the depth interval.

The flux $q_x(0)$ at the surface was assumed to be zero for both nutrients and Chl-a. To visualize the Chl-a response concerning TN and TP, ordinary regression was used to model Chl-a as a function of TN and TP where linear, squared predictor was included. These relationships were also considered in the vertical and seasonal valuations. Seasons were defined as spring (March-May), summer (June-August), autumn (September-November), and winter (December-February). TP, TN, and Chl-a fluxes were represented by average monthly values and the change between the monthly integrals was represented by the value at the end of the former month or the first of the latter month. With local smoothing to grid data, this smoothing scheme begins by setting X_1 to x_1 , where X_i stands for smoothed observation and x stands for original observation. The subscripts refer to the period, where the smoothed series started with the smoothed version of the second observation. For time interval d between the closest measurements, the smoothed value is found by calculating:

$$X_i = \frac{x_{i-1}d_{i+1} + x_i(d_i + d_{i+1}) + x_{i+1}d_i}{2(d_i + d_{i+1})} \quad (2)$$

with $i \geq 2$.

Mass of nutrient and Chl-a in each water column were estimated from flux profile:
 $\text{Mass} = \text{flux } (\text{mg m}^{-2} \text{ day}^{-1}) * \text{area of north basin } (\text{m}^2) * 365 \text{ (day year}^{-1}\text{)}$

Statistical analyses. The correlation coefficient, r was calculated using Microsoft® Excel 2019. Critical levels of the correlation coefficient serve as the foundation for the statistical test for significance. Spearman's correlation coefficients were calculated between the phytoplankton-related variable (Chl-a) and nutrients variables (TN and TP).

Results and Discussion

Seasonal environmental status. The panels show total mixing in the water column as a result of monomictic turnover occurring from February to March. The thermocline and lower hypolimnion were followed by higher concentrations of TP, TN, and SiO_2 , or lower values of Chl-a, pH, water temperature, and DO until the next spring's turnover. TP

imports began to decline from the second period, and the concentration of TP increased from June to August. TP was lowest in the thermocline and accumulated in the bottom, especially in winter during the given periods. The average values were 0.0074, 0.0059, 0.0098 mg L⁻¹ for epilimnion, thermocline, and hypolimnion, respectively. In recent years (period V), the resuspension of TP from lower to upper water layers was observed again in spring, albeit at a lower concentration than before. However, the accumulated nutrient in the bottom is still higher than it was during another time period, from autumn to winter. Other studies reported the TP trend to be oligotrophic (Hsieh et al 2010; Kishimoto et al 2013). The time series of TN in Lake Biwa revealed that TN increased rapidly from period II onward; the highest TN concentration was observed in period IV, however, it decreased after period V. In the upper layer, TN increased from January to June but dropped from July with lowest recorded value in October. TN, on the other hand, accumulated in the hypolimnion from the first to the last period, particularly in autumn and winter. Period IV revealed that TN concentration was up to 0.45 mg L⁻¹ from last August to December before decreasing the same level with other previous years in period V. In period IV, it reached the highest concentration of TN compared to other periods. Kishimoto et al (2013) and Shrivastava (2014) found that TN trended towards eutrophication before 2000 but seemed to reverse after 2003. It was observed that nutrient loading has gradually decreased and then stabilized since 1985 as a result of a successful governmental water treatment regulation implemented in 1982 (Kumagai 2008). These reports were similar to the trend seen in our data. In period II, the nutrients were depleted in the epilimnion. This can be explained by the little rainfall and well-developed thermocline (Sohrin et al 1996). Chl-a data show that the concentration varied greatly in the period I compared to periods IV and V; however, periods II and III showed a stable trend. Overall, the Chl-a concentration decreased during time observation, from 3.63 µg L⁻¹ in the first period to 1.44 µg L⁻¹ in recent investigation. In vertical analysis, Chl-a is high in water surface and decreased in lower layers, average 3.95 µg L⁻¹ for epilimnion and 0.97 µg L⁻¹ for hypolimnion. Furthermore, Figure 2 depicts the transition of Chl-a concentration, which represents phytoplankton biomass over the course of 35 years. It rises gradually in the spring, reaches a peak in October, and then falls in the winter (period I and II). The shift changed from period III onwards, increasing from spring, peaking in summer, then decreasing in autumn and winter. The trend of silicate concentration has significantly increased and appears to be changing over time. It has a high value in the spring and a low value in the other seasons from period III, while gradually increasing from the spring in periods I and II. On the other hand, silicate from Figure 2 shows that the accumulated budget is increasing from the beginning and reaches its highest value in the last period (4-4.5 mg L⁻¹) from September to December.

Figure 2 continuously shows that the water quality data exhibited significant seasonal variability in the north basin of Lake Biwa for every seven years (period I–V). pH was stable across the five periods and fluctuated according to the season: high in the summer, reach the peak in July-August, and low in the winter and spring. Vertical value also indicated the difference among water layers, high in the epilimnion, and low in the hypolimnion with an average of 7.3. The figure revealed that pH was increased in period III compared to other periods. The DO increased in the spring and summer (highest value in March and April), fluctuated around 8.54 to 9 mg L⁻¹, and then decreased gradually in autumn and winter (November and December), with high values at the surface and low values at the bottom, with little fluctuation from year to year. However, DO concentration increased in period III and period V but decreased in period I and IV. The water temperature ranged between 6.31 and 28.4°C, highest in August. The average photic zone temperature was 14.3°C in period I and 15.3°C in period V. According to Kishimoto et al (2013), the annual mean water temperature increased steadily at a rate of 0.045°C per year during two decades from 1980 to 2010. The mean increase in water temperature in the stratification period is higher than in the circulation period (0.058°C and 0.037°C per year, respectively).

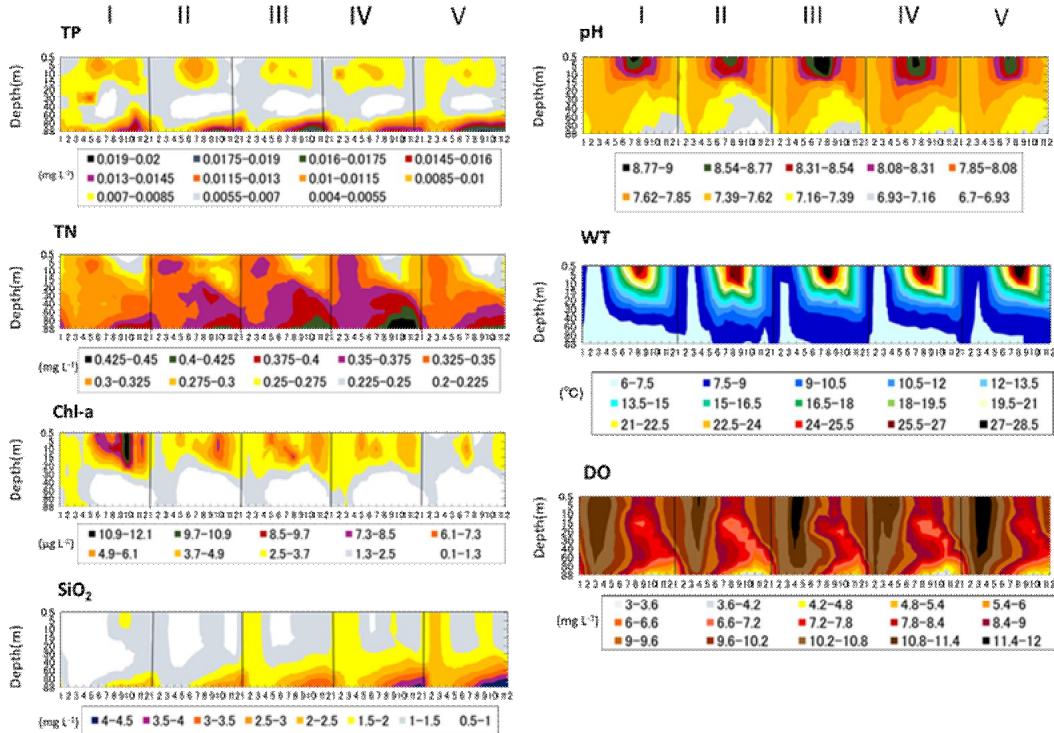


Figure 2. Monthly-vertical patterns of variable contours of TP, TN, Chl-a, SiO₂, WT, pH, and DO. Average was done in periods of 7 successive years for successive five periods, which are period I (1980-1986), II (1987-1993), III (1994- 2000), IV (2001-2007), and V (2008- 2015).

Seasonal variation of phytoplankton biomass. The density of phytoplankton species was determined by using the method proposed by Ichise et al (1999). The total biovolume density was converted into wet weight biomass by multiplying the biovolume by the water density. From 1979 to 2009, the total biomass in annual was studied, and it was dubbed S-nano for small nano phytoplankton ($< 100 \mu\text{m}^3 \text{cell}^{-1}$), L-nano for large nano phytoplankton ($100-4000 \mu\text{m}^3 \text{cell}^{-1}$), Net for net phytoplankton ($\geq 4000 \mu\text{m}^3 \text{cell}^{-1}$), as followed by Kishimoto et al (2013). Figure 3 shows the variation in wet weight biomass of phytoplankton and reveals an apparent decrease in phytoplankton occurrence during the study period. The biomass decreased rapidly in the 1980s before increasing gradually during the 1990s and finally displayed a decreasing trend from 2000.

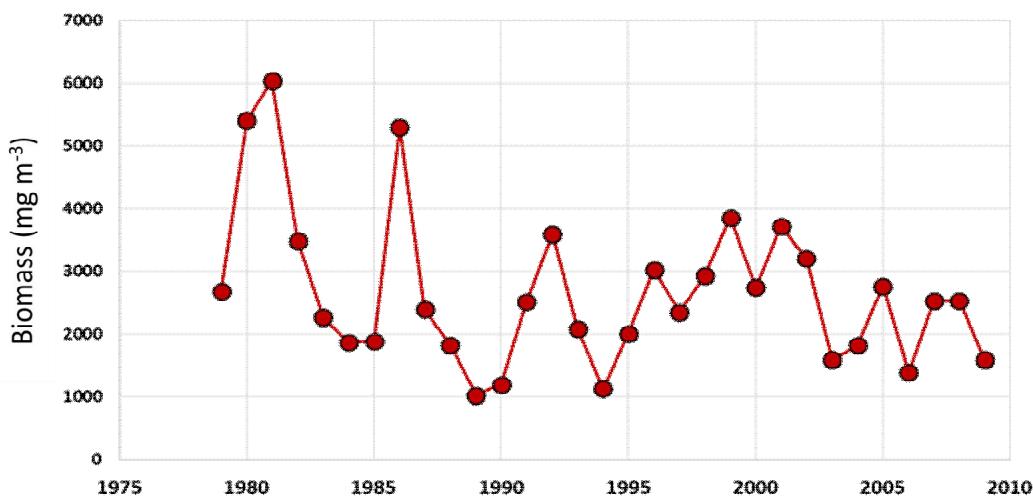


Figure 3. Long-term annual phytoplankton biomass in the North Basin of Lake Biwa.

The inter-annual variation in seasonal biomass during the study period is indicated in Figure 4. The result summarized that the trend in seasonal biomass fluctuated differently due to each season. During the study period, the biomass tended to slightly increase while the biomass in summer remained almost constant but gradually decreased in autumn. In general, biomass in summer and autumn was higher than in spring and winter. In particular, it is evident that biomass in the seasonal fluctuation side was similar in the recent year compared to the past, with the exception of blooming time in summer.

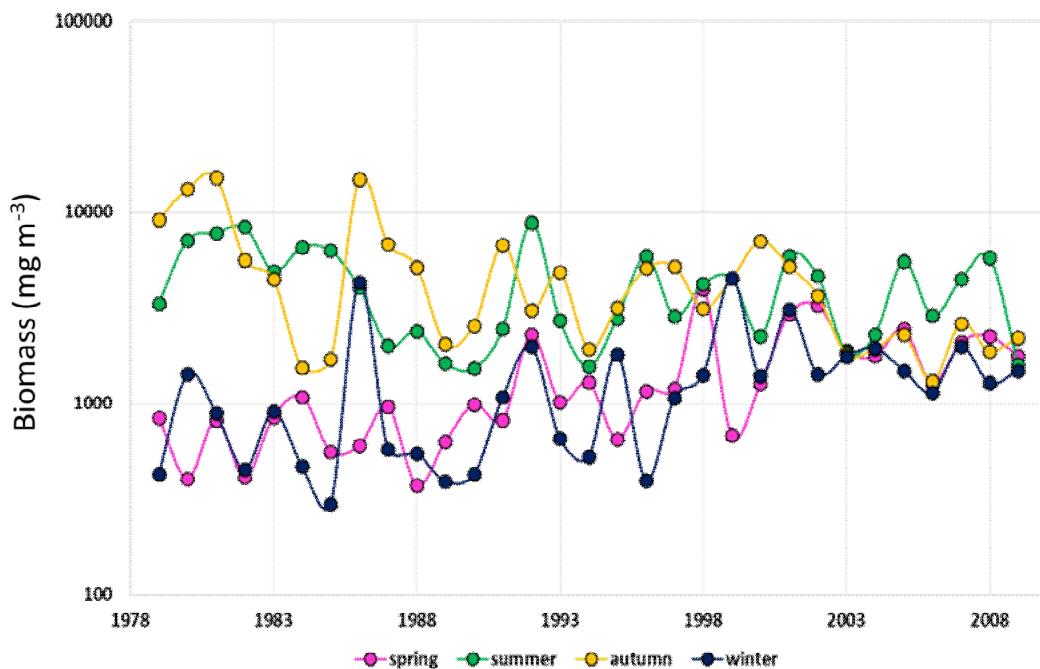


Figure 4. Seasonal variation in phytoplankton biomass.

Figure 5 demonstrated the transition in the seasonal variation of the biomass of each size of phytoplankton species. The biomass of small phytoplankton was extremely low in the first period, but it tended to increase gradually and change the percentage of the population from autumn to summer from 1997 onward. Nevertheless, the large phytoplankton fluctuated its population during the study period and slightly decreased in the recent years. The clear transition of blooming season from summer to autumn and spring started from 1998. In contrast, the net phytoplankton biomass was highest in the first decade but revealed a rapidly decreasing trend during the remaining period. Furthermore, it is apparent to see that the blooming season of phytoplankton changed from autumn to summer in the decade of 1990s and 2000s. Generally, the biomass of species of three sizes was high in summer and autumn and low in winter and spring.

Vertical and seasonal variation in Chl-a and nutrients fluxes. The monthly flux profiles are shown as a seasonal change of Chl-a, TN, and TP in Lake Biwa. The Chl-a flux is positive in the photic zone (0-20 m) from March to May as spring blooms with the thermal stratification development (Figure 6). The flux is weakly negative from June to August, which is possible due to a divergence of the convective circulation of the thermally induced gyre in the epilimnion and depletion of nutrients. The bloom of cyanobacteria is transported offshore and stays at the surface of the down-welling center of the gyre (Ishikawa et al 2002). From September to October, the flux is also positive, and it steepens gradually from the surface to the bottom. When a settling period begins after this internal wave activity, organic matter sinks constantly from the upper to lower layers. The negative flux is observed when Chl-a decreases gradually by the decomposition process during winter from December to February. Figure 6, point A shows the blooming time that occurs leads to increasing biomass. Figure 6, point B shows the

strong activity of gyre in epilimnion and thermocline, which prevent the sinking of biomass and separation of the density of phytoplankton. Figure 6, point C shows the occurrence of the sinking process from thermocline to the hypolimnion by a part of the effect of internal waves. Figure 6, point D shows the decomposition process in a 30 m depth of water column.

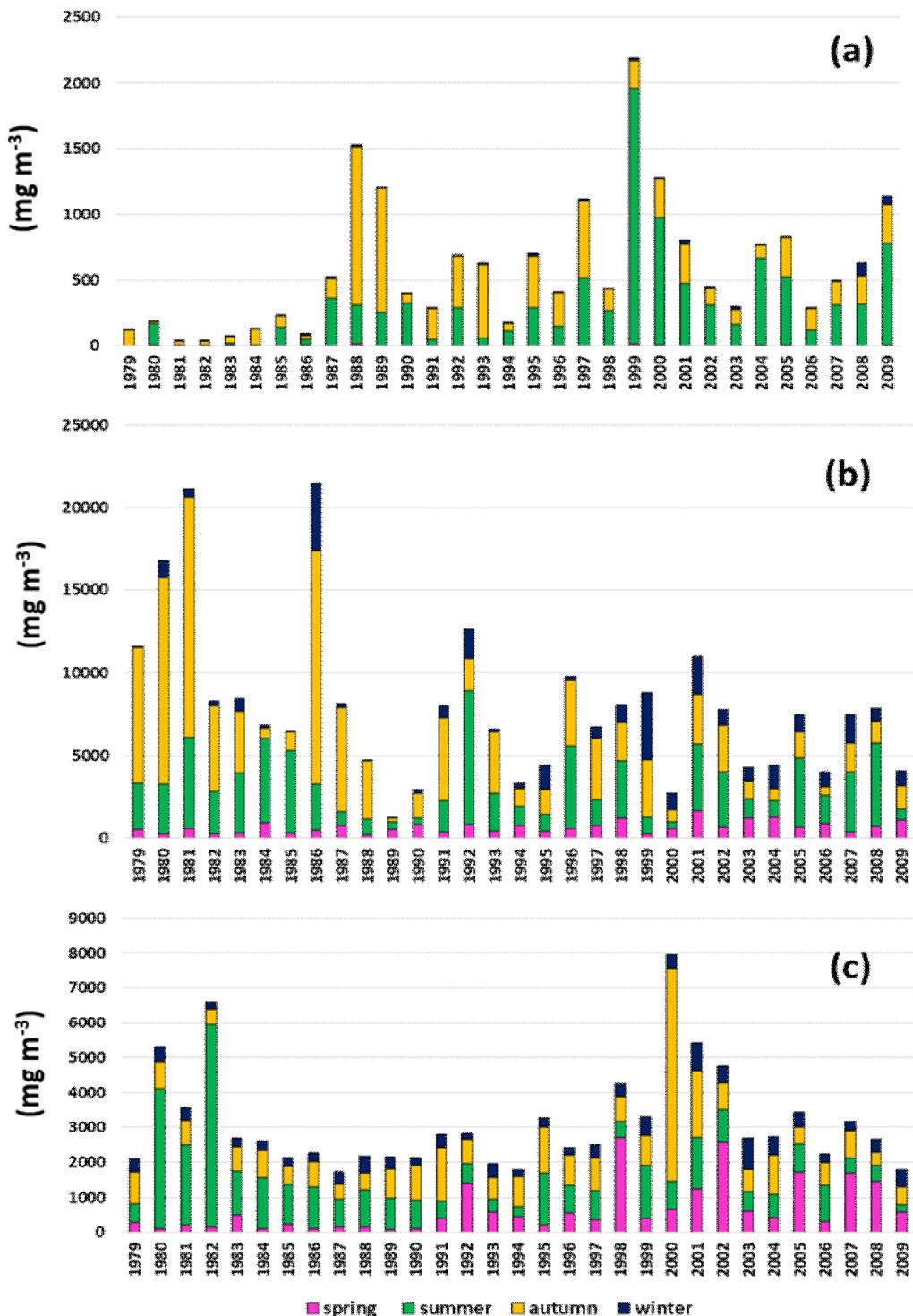


Figure 5. Seasonal variation in the varied sizes of biomass for each size. (a) S-nano: small nano phytoplankton ($< 100 \mu\text{m}^3 \text{cell}^{-1}$), (b) L-nano: large nano phytoplankton ($100-4,000 \mu\text{m}^3 \text{cell}^{-1}$), (c) Net: net phytoplankton ($\geq 4,000 \mu\text{m}^3 \text{cell}^{-1}$).

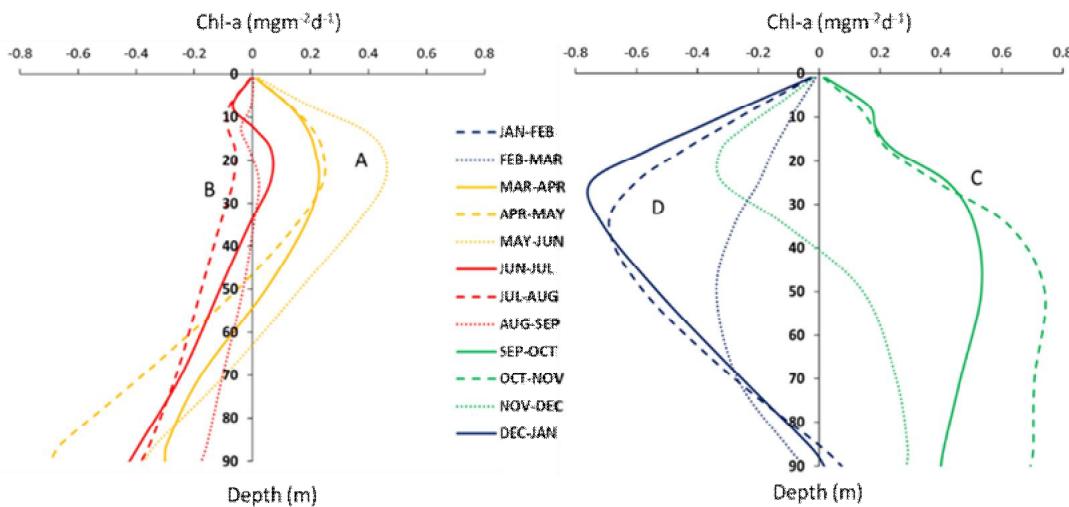


Figure 6. Average vertical profile of Chl-a flux, the positive period from spring to early autumn, and a negative period from late autumn to winter during the 5 periods.

Interestingly, positive TN flux in winter shows an inverse trend when compared to Chl-a flux; it is positive in the upper layers from October to February, then rapidly decreases from March to become negative during spring and summer. TN is consumed strongly from June to July from 10 m to 20 m in depth (Figure 7). During the bloom, the TN is used by algae but then increased. The removal of N from lakes is usually dominated by denitrification concomitantly with the oxidation of organic matter, but in highly productive surface waters, high pH would favor N release to the atmosphere as NH₃. The decrease from May to October could be a result of this denitrification. Meanwhile, the TP flux exhibits an in-depth variation that decreases abruptly in the last 10 m during the winter, a minor increase at deeper layers (40-70 m), followed by a major decrease in the hypolimnion. The positive flux is observed in the upper layer (0-30 m) in spring and hypolimnion in summer and autumn (Figure 8). From June to November, especially from September to November, TP is lost (negative) in the photic layer and gained (positive) in the anaerobic environment.

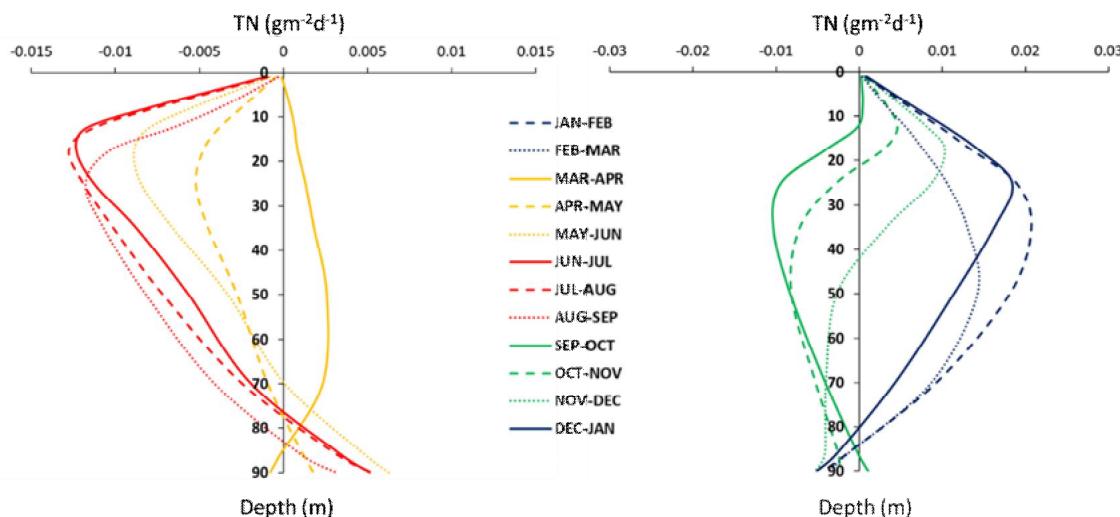


Figure 7. Average vertical profile of TN flux, the positive period from mid-autumn to winter, and the negative period from spring to early autumn at 0 to 90 m during the 5 periods.

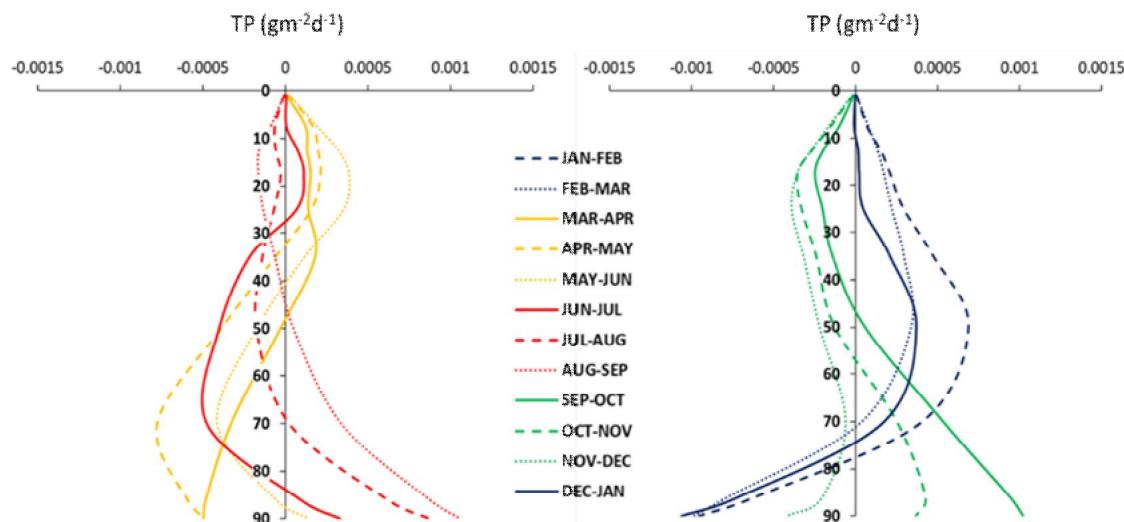


Figure 8. Average vertical of TP fluxes divided into 2 parts, the positive period from winter to early summer and the negative period from late summer to autumn during the 5 periods.

The relationship between the fluxes of TP and Chl-a was evidenced in the epilimnion and hypolimnion (Figure 9). $\Delta \text{Chl-a} > 0$ and $\Delta P > 0$ in the surface layers are due to photosynthesis, which is elevated between March and May before reducing gradually in the thermocline. Positive values for both Chl-a and TP suggested active photosynthesis (production) and nutrient addition. Specifically, Chl-a and TP were both negative in the summer from the surface to the thermocline, which correlates to the activity of the thermally induced gyre in the epilimnion. From September to November, $\Delta \text{Chl-a} > 0$ and $\Delta P < 0$ at the surface were positive in the hypolimnion, suggesting that production occurred due to physical processes. The pattern was negative on the surface during the winter, but it was still produced in the bottom before experiencing the opposite fluctuation from top to bottom during January and February. The fact that both nutrients and Chl-a were negative at the bottom indicates that no major production or decomposition was taking place. Nutrients were stored or adsorbed in the water, but earlier in the top and later in the bottom.

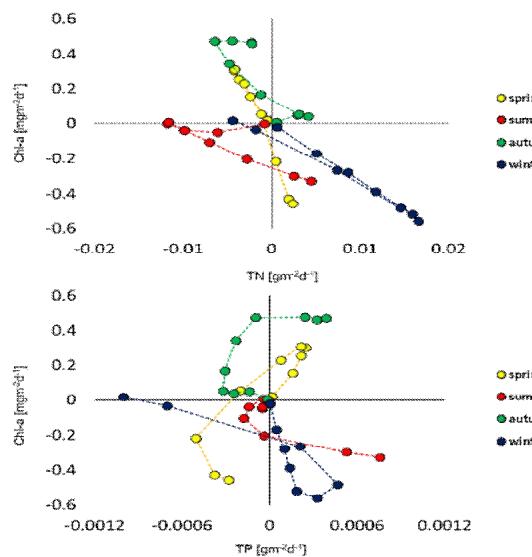


Figure 9. The relationship between the fluxes of Chl-a, TN, and TP in water columns. Each point represents the water depth from 0 to 88 m.

The results presented in Figure 9 also describe the season-dependent relationship between TN and Chl-a, similar to TP and Chl-a. The Chl-a flux was negative during the summer because of the loss of TN and TP and the increased concentration of nutrients. Biomass dropped in the summer and caused a decrease in the total nutrients with the activity of strong physical process as gyres. The opposite trend was observed in the data during the winter when the nutrient flux was positive, but the Chl-a flux was negative. During the autumn and spring, the Chl-a flux was almost positive, while the TN flux was negative in the spring and positive in the autumn. The TP flux, in contrast, was positive in the spring but negative in the autumn. When TP concentration decreased (negative flux) in the summer and autumn, the relationship between TN and Chl-a (R^2 summer = 0.69, R^2 autumn = 0.75; $p < 0.05$) was significant weaker than cooling period (R^2 winter = 0.98, $p < 0.05$) (Table 1). The effect of TP and TN on Chl-a was considered significant, indicating that TN was strongly related to Chl-a when TP was high and less so when TP was low. The effect of TN on the TP-Chl-a relationship was not evident. During the summer and autumn seasons, the concentration of TN decreased and then increased in the winter; the correlation among these three patterns of TP-Chl-a was similar (R^2 winter = 0.62, R^2 summer = 0.69, R^2 autumn = 0.46, $p < 0.05$) (Table 1). These data indicate that while the effects of the TN and TP as nutrient resources on phytoplankton biomass are both considerable and relevant, TP plays a bigger role, suggesting that TP rather than TN, limits Chl-a. Filstrup & Downing (2017) discussed that Chl-a and TN relationship differed depending on TP concentration and it covaried with both TN and TP. Chl-a had a stronger and novel relationship with TN in hypereutrophic conditions ($TP > 100 \text{ g L}^{-1}$) but not in mesotrophic or eutrophic conditions ($TP \leq 100 \mu\text{g L}^{-1}$). The finding supports an argument that the effect of TN on Chl-a is little at low TP but stronger in TP-rich lakes (Canfield et al 1985; McCauley et al 1989).

Table 1
Spearman's correlation at $p < 0.05$ result between Chl-a and TN and TP during the study periods

Variables	Chl-a			
	Spring	Summer	Autumn	Winter
TN	0.97	0.69	0.75	0.98
TP	0.78	0.69	0.46	0.62

Chl-a and nutrient mass remaining in the water column. After calculating the flux profile of Chl-a and nutrient, the difference in seasonal mass (ton month^{-1}) would be estimated to clarify the supply rate via nitrification and removal rate via assimilation and denitrification. Figure 10 shows that the inventory of Chl-a, TN, TP remaining in the lake in the interval of each month was varied.

The vertical profile shows the interval difference of supply and removing TN mass ranged from -0.18 to 177 ton month^{-1} in the epilimnion, from -208 to 533 ton month^{-1} in the metalimnion, and -87 to -100 ton month^{-1} in the hypolimnion. It means the mass change was very different in the upper and middle layer while small in the lowest layer for TN. Similarly, the vertical profile of supply and removing Chl-a mass fluctuated from -8.7 to 10.8 ton month^{-1} in the epilimnion, -19.4 to 22.5 ton month^{-1} in metalimnion and -16.4 to 21 ton month^{-1} in the hypolimnion. The highest mass exchange occurred in the thermocline. For TP mass, we estimated that -0.08 to -5.27 ton month^{-1} in the epilimnion, 0.4 to 17.5 ton month^{-1} in metalimnion, and -0.89 to -22.5 ton month^{-1} in hypolimnion was unexpected.

In terms of seasonality, the TN mass was recovered during the winter by nitrification before being lost in early March for metabolism in the epilimnion during the summer and early autumn. Meanwhile, the deposit of TP was high in winter and early spring but the shortage was seen in summer and late autumn.

Tsunogai et al (2018) stated that assimilation accounted for 75% of N metabolism (primary production) and assumed that nitrification at the surface of 15 m (epilimnion and upper thermocline) supplied the N required for assimilation. This point expresses the gain and loss of mass in these layers was very strong. Their study, on the other hand,

discovered that the supplied/removed ratio was 0.6 in spring, 0.9 in summer, and 1.5 in autumn before decreasing 0.6 in winter. The areal assimilation rate increased from spring to summer and decreased in autumn and winter.

Yoshimizu et al (2002) showed that only 44% P uptake by algae was recycled within the lake, the high mass observed in the bottom shows most of the P settled to the bottom and was fixed in the sediments of the lake. The P release from the bottom of the lake could be responded to the recovery of P.

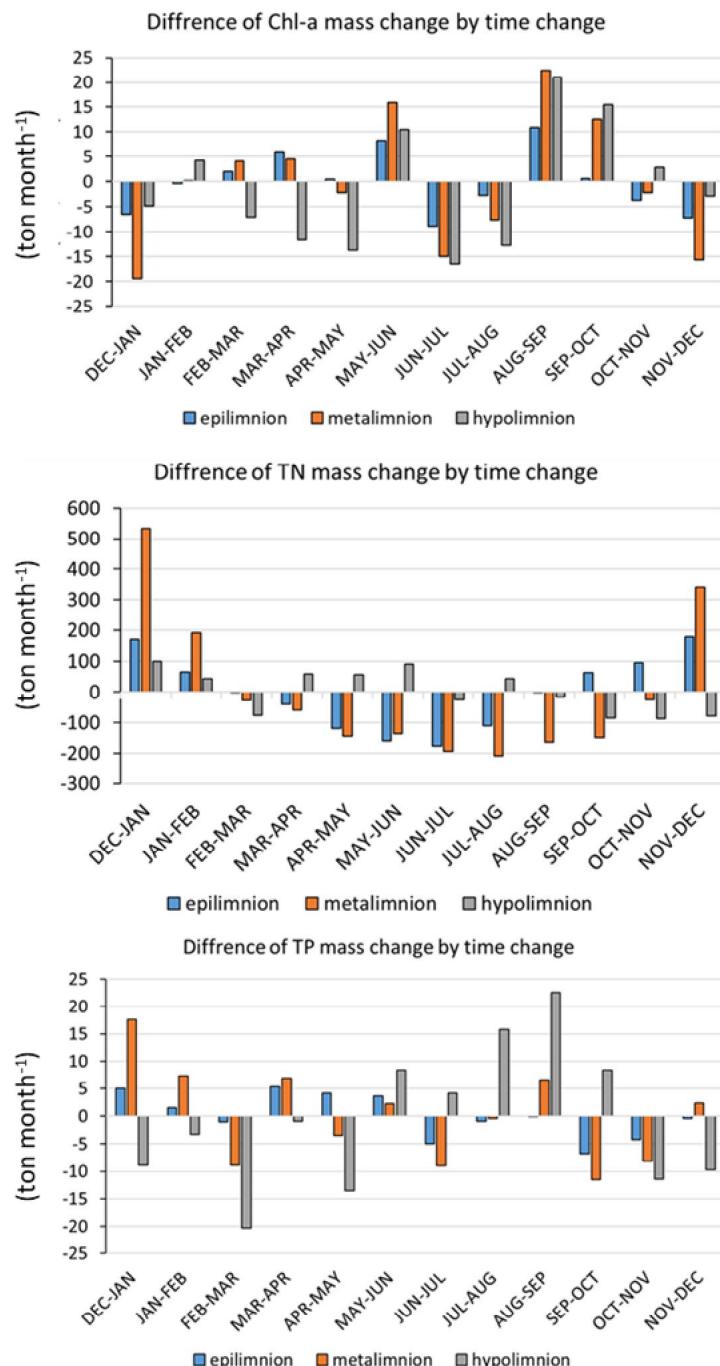


Figure 10. The monthly deposition and vertical distribution of the remaining mass of nutrient and Chl-a.

Seasonal-vertical N:P ratio in Lake Biwa. Lake Biwa has been classified as one of the phosphorus-limited lakes (Tezuka 1992). To predict algal biomass and composition, the N:P ratio in lentic systems has been often used as a key indicator (Tilman 1982). Nutrients are well known as the primary nutrients for phytoplankton and are typically limiting factors in algal growth; thus, the N:P ratio is used to compare the availability of these nutrients. Furthermore, this ratio has the potential to become a useful method for calculating the trophic state index of lakes (Grzetic & Camprag 2010). However, the N:P ratio has been a problematic and messy variable for limnology. It is a ratio variable and, therefore, is not a good state variable to study lake processes. It usually varies inversely with lake trophic state and biological standing stocks (Downing & McCauley 1992; Quiros 1990). However, because the N:P ratio and trophic status are closely and inversely related in lakes, the N:P ratio may be a good variable to study state change in lakes. The atomic ratio, 16N:1P, which is known as the Redfield ratio, has been used for marine and freshwater phytoplankton studies to describe the average elemental composition. It has been suggested that a mass N:P ratio above 17 indicates P limitation, a ratio below 10 shows N limitation, and values between 10 and 17 indicate that either of the nutrients may be limiting (Ulén 1978; Hellström 1996).

A plethora of hypotheses have been proposed in order to demonstrate that the N:P ratio can explain the lake's status. For instant, an N to P ratio $\leq 10:1$ appears to favor algal blooms, especially blue-green algae. On the other hand, one of the most recognized theories, the low N:P hypothesis (Bulgakov & Levich 1999) predicts that cyanobacteria will dominate lakes.

Figure 11 shows that N:P ratios in Lake Biwa, which are used to indicate phosphorus deficiency, are typically higher than the Redfield ratio (16). All values of the N:P ratio in the whole layer were higher than 50. The N:P ratio increased as P decreased at 40 m depth, then decreased to the normal value as P increased near the floor. Moreover, the N:P ratio varied in each season; the value was highest in spring and lowest in autumn in the epilimnion but was converted in the hypolimnion. According to Ichise et al (2001), the mean of N:P ratios in the north basin increased from 67 to 104 from 1979 to 1999 with the decrease of the population of phytoplankton. Nakanishi et al (2001) reported that these values were found to be 77 and 134 during 1980-1992 and 1993-2000, respectively. Shrivastava (2014) concluded that TN: TP in the northern basin is 76 from 1963 to 2008.

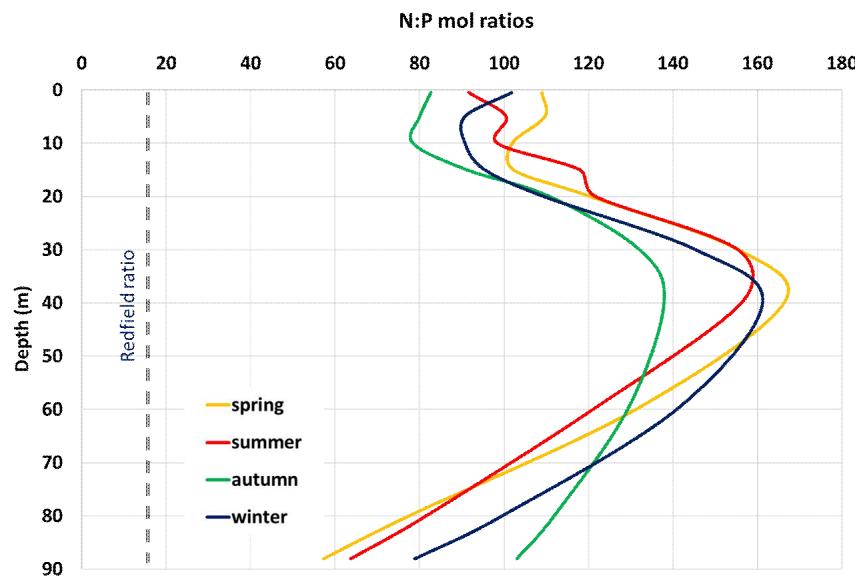


Figure 11. Seasonal-vertical N:P ratios in the North basin, Lake Biwa.

The ratio assumes that algal growth is rapid in the photic zone, then the increasing trend of the N:P ratio in the metalimnion indicates that nitrogen input increases slightly or that

phosphorus disappears from the water, which could be a limiting factor for algal growth at this layer. Subsequently, this decrease in the ratio may be related to the rate of P liberation from sediments and increased rates of N loss (i.e., denitrification). Denitrification was the most important mechanism for reducing N:P ratios in the water column, while both nitrogen fixation and sediment resuspension raised N:P ratios. The ratio of the nutrient can markedly influence the community structure of the phytoplankton (Tilman 1982). Based on the N:P ratio, it is likely that almost all phosphorus entering the lake is transported to the bottom sediment and fixed there without being recycled, with P assimilation in the upper layers in the spring and accumulation in the lower layers in the autumn. A level of phosphorus annually into and retained in lake Biwa falls as particulate phosphorus to the lake bottom.

The impact of the increase of N:P ratios on the lake ecosystem is unknown. However, the fact that this ratio was higher than in other lakes appeared to be one of Lake Biwa's significant limnological characteristics (Nakanishi et al 2001). Future studies should examine the response and adaptation of lacustrine organisms to the N:P increase. Previous ecological studies of the other lakes suggested that N:P ratios can affect the species composition, phytoplankton, and zooplankton (Elser & Hassett 1994; Jeppesen et al 2000).

Conclusions. Seasonal series data of water quality in Lake Biwa's north basin, analyzed from 1980 to 2015 and divided into five periods, have been described, indicating that the lake's trophic status has changed. As a result, it was discovered that TP and TN concentrations were still decreased, and nutrient accumulation in the bottom area was higher than before, despite the fact that the resuspension process occurred recently in terms of TP. Phytoplankton biomass indicated by Chl-a data revealed the collapse and response of phytoplankton species due to the fluctuation of nutrient changes and physical factors during the analyzing period. The season-specific Chl-a profile generated in this study concluded that the vertical flux profiles of TP and TN were compared, and a definite difference was found especially in the inversion of TN and Chl-a in winter time. Seasonal events in the flux profiles are described. Although the mechanism of the relationship needs to be studied further, the relationship between Chl-a and TN, TP fluxes suggests that Chl-a fluxes can be negative or positive depending on the fluctuation of TN, TP fluxes. The effects of the TN and TP nutrient resources on Chl-a are both considerable and relevant, however, TP plays a more important role than TN to Chl-a. Finally, we can deduct from the flux profile how much nutrients and Chl-a have remained in each layer and season. The mass change for TN was very different in the upper and middle layers, while it was small in the lowest layer, with a wide range in the metalimnion for Chl-a and a variable range in the hypolimnion for TP. N:P ratios in Lake Biwa were high in the metalimnion, ranging from 83 to 108 (highest in spring and lowest in autumn) in the surface area, but decreasing from 57 to 103, (highest in autumn, and lowest in spring) in bottom layers.

Conflict of interest. The authors declare that there is no conflict of interest.

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