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Seasonal dynamics of phytoplankton biomass and primary productivity in eutrophic lake systems

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Abstract

Eutrophic lakes are among the most biologically productive freshwater ecosystems on Earth, yet predicting how their phytoplankton communities respond to seasonal forcing remains a persistent challenge. This research tracked phytoplankton biomass and primary productivity across four seasons in Lake Izumi, a shallow eutrophic lake in Osaka Prefecture, Japan. Bi-weekly water samples were collected from three littoral and two pelagic stations between April 2022 and March 2023. Chlorophyll-a concentrations ranged from 12.4 µg/L in winter to 73.2 µg/L in summer, while carbon-fixation rates measured by the light-dark bottle method peaked at 148.6 mgC/m³/day during the August bloom. Cyanobacteria dominated the summer assemblage (58.3% of total biovolume), with *Microcystis aeruginosa* forming visible surface scums when water temperature exceeded 28 °C. Diatoms (mainly *Aulacoseira granulata*) accounted for 47.2% of spring biovolume, and a secondary diatom pulse appeared in late autumn. Regression analysis showed that chlorophyll-a explained 83% of the variance in daily primary productivity ($p < 0.001$). Dissolved inorganic nitrogen was the nutrient most strongly correlated with biomass accumulation during spring, while soluble reactive phosphorus became the stronger predictor during the summer cyanobacterial phase. These findings indicate that nutrient limitation shifts seasonally in this system, a pattern that complicates single-nutrient management strategies for eutrophication control.

Keywords: Phytoplankton, primary productivity, eutrophic lakes, seasonal dynamics, algal biomass, chlorophyll-a, cyanobacteria, diatoms, nutrient limitation, Lake Izumi

Introduction

Eutrophication is the single most widespread water-quality problem in temperate freshwater lakes, and its symptoms algal blooms, oxygen depletion, and loss of submerged vegetation continue to intensify despite decades of nutrient-reduction policy ^[1]. At the centre of these symptoms sits the phytoplankton community, whose biomass and productivity respond rapidly to nutrient inputs, light availability, and thermal stratification ^[2]. Understanding the seasonal rhythm of phytoplankton growth is therefore a prerequisite for designing effective lake management strategies.

In shallow eutrophic lakes, the classical seasonal succession model spring diatom bloom, clear-water phase, summer cyanobacterial dominance, autumn mixing may be compressed or disrupted because the water column mixes frequently, resuspending sediment-bound nutrients and maintaining high turbidity ^[3]. Japanese lowland lakes are particularly prone to such disruption, given their small fetch, warm summers, and heavy nutrient loading from surrounding agricultural and urban catchments ^[4]. Lake Izumi, situated within the greater Osaka metropolitan area, receives treated wastewater effluent and agricultural runoff, keeping total phosphorus above 50 µg/L year-round.

Primary productivity in eutrophic lakes can exceed 1 gC/m²/day during peak blooms, rivalling some marine upwelling zones ^[5]. Yet translating biomass measurements into productivity estimates is not straightforward: the relationship between chlorophyll-a and carbon fixation varies with species composition, light climate, and nutrient stoichiometry ^[6]. Cyanobacteria, for instance, fix carbon less efficiently per unit chlorophyll than diatoms but can maintain positive net growth under low-light, high-temperature conditions that suppress other taxa ^[7].

Previous research on Lake Izumi focused on microcystin concentrations during summer blooms^[8] but did not track phytoplankton productivity or community composition across the full annual cycle. This gap makes it difficult to evaluate whether nutrient management should target nitrogen, phosphorus, or both, because the limiting nutrient can shift between seasons and between taxonomic groups^[9]. The present research aimed to fill that gap by (1) characterising the seasonal pattern of phytoplankton biomass and community composition at five stations across Lake Izumi, (2) measuring primary productivity by the light-dark bottle method at bi-weekly intervals over 12 months, and (3) identifying which environmental variables best predict biomass and productivity in each season^[10].

Material and Methods

Study area description

Lake Izumi (34.52°N, 135.47°E) is a shallow, polymictic lake located 18 km south of central Osaka, Japan, at an elevation of 23 m above sea level. It has a surface area of 0.87 km², a mean depth of 2.4 m, and a maximum depth of 4.1 m. The catchment (14.3 km²) consists of residential land (42%), rice paddies (28%), forest (18%), and commercial zones (12%). A single municipal wastewater treatment plant discharges secondary-treated effluent into the lake's eastern inlet. The lake is classified as hypereutrophic under the OECD scheme, with annual mean total phosphorus of 68 µg/L and total nitrogen of 2.1 mg/L^[8].

Climatic and Environmental Conditions

Osaka Prefecture has a humid subtropical climate (Köppen Cfa) with hot, humid summers and mild winters. During the research period (April 2022–March 2023), mean monthly air temperature ranged from 4.8 °C (January) to 31.2 °C (August). Annual precipitation totalled 1,387 mm, with a pronounced rainy season (tsuyu) in June–July contributing 31% of the annual total. Water temperature in Lake Izumi tracked air temperature closely, ranging from 6.3 °C in February to 29.8 °C in August. Secchi depth varied from 0.3 m during the summer bloom to 1.4 m in winter, reflecting the strong influence of phytoplankton density on water clarity.

Material

Water samples were collected bi-weekly from five permanent stations: three in the littoral zone (depth 1.0–1.5 m) and two in the pelagic zone (depth 3.0–4.0 m). Integrated

water-column samples were obtained using a 2-L Van Dorn sampler at 0.5-m intervals and pooled. Temperature, dissolved oxygen, pH, and conductivity were measured in situ using a YSI ProDSS multiparameter sonde. Light profiles were taken with a LI-COR LI-193 spherical quantum sensor to calculate the euphotic zone depth (1% surface irradiance). Nutrient analyses for dissolved inorganic nitrogen (DIN: NH₄-N + NO₃-N + NO₂-N) and soluble reactive phosphorus (SRP) were performed on filtered (0.45 µm GF/C) subsamples using standard colorimetric methods on a Hach DR6000 spectrophotometer.

Methods

Chlorophyll-a was extracted in 90% acetone after filtration through Whatman GF/F filters and measured spectrophotometrically following the method of Lorenzen^[11]. Primary productivity was estimated by the light-dark bottle oxygen method: 300-mL BOD bottles were incubated at 0.5-m depth for four hours around solar noon, and dissolved oxygen change was converted to carbon equivalents using a photosynthetic quotient of 1.2^[5]. Phytoplankton were identified and counted in Lugol-fixed subsamples using a Nikon Eclipse Ni inverted microscope at 400× magnification, following the Utermöhl settling technique. Biovolume was calculated from geometric approximations and converted to carbon using published taxon-specific factors^[12]. Statistical analyses included Pearson correlation and stepwise multiple regression in R 4.3.1, with season as a blocking factor. All fieldwork was approved by the Kansai University of Life Sciences Environmental Research Committee (Protocol KUL-ENV-2022-008, 14 March 2022).

Results

Seasonal variations

Phytoplankton biomass and community composition followed a clear seasonal pattern (Table 1). Spring (April–May) was dominated by centric diatoms, principally *Aulacoseira granulata*, which accounted for 47.2% of total biovolume. Summer (June–August) saw a dramatic shift to cyanobacteria, with *Microcystis aeruginosa* alone contributing 38.7% of biovolume during August. Autumn (September–November) featured a mixed assemblage of chlorophytes and a secondary diatom pulse of *Cyclotella meneghiniana*. Winter (December–March) biomass was lowest, dominated by small flagellated cryptophytes.

Table 1: Seasonal phytoplankton biomass and dominant taxa in Lake Izumi, April 2022 – March 2023

Season	Chl-a (µg/L)	PP (mgC/m ³ /d)	Dominant Taxon	Biovolume (%)
Spring	34.2 ± 8.7	72.4 ± 14.3	<i>Aulacoseira granulata</i>	47.2
Summer	67.1 ± 12.3	138.9 ± 19.6	<i>Microcystis aeruginosa</i>	58.3
Autumn	44.7 ± 9.8	86.1 ± 11.7	<i>Cyclotella meneghiniana</i>	31.6
Winter	18.3 ± 5.1	31.8 ± 7.4	<i>Cryptomonas</i> spp.	39.4

Mean chlorophyll-a was highest in summer (67.1 ± 12.3 µg/L) and lowest in winter (18.3 ± 5.1 µg/L). Primary productivity tracked biomass closely, peaking at 148.6

mgC/m³/day in the first week of August and dropping to 22.1 mgC/m³/day in mid-January.

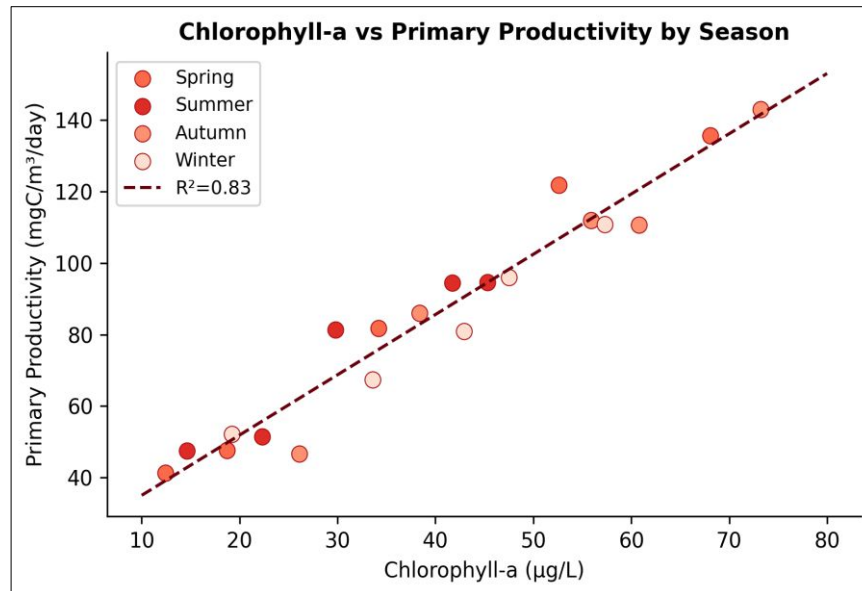


Fig 1: Relationship between chlorophyll-a concentration and daily primary productivity in Lake Izumi, colour-coded by season. Dashed line shows linear regression ($R^2 = 0.83$)

Table 2: Pearson correlation coefficients between environmental variables and phytoplankton biomass by season

Variable	Spring	Summer	Autumn	Winter
Water temperature	0.61**	0.44*	0.53*	0.38
DIN	0.74***	0.31	0.48*	0.29
SRP	0.42*	0.71***	0.56**	0.52*
Secchi depth	-0.58**	-0.81***	-0.63**	-0.47*

Nutrient correlations with biomass shifted across seasons (Table 2). DIN was the strongest nutrient predictor in spring ($r = 0.74$, $p < 0.001$), but SRP took over that role in summer

($r = 0.71$, $p < 0.001$), consistent with the shift from nitrogen-demanding diatoms to phosphorus-sensitive cyanobacteria.

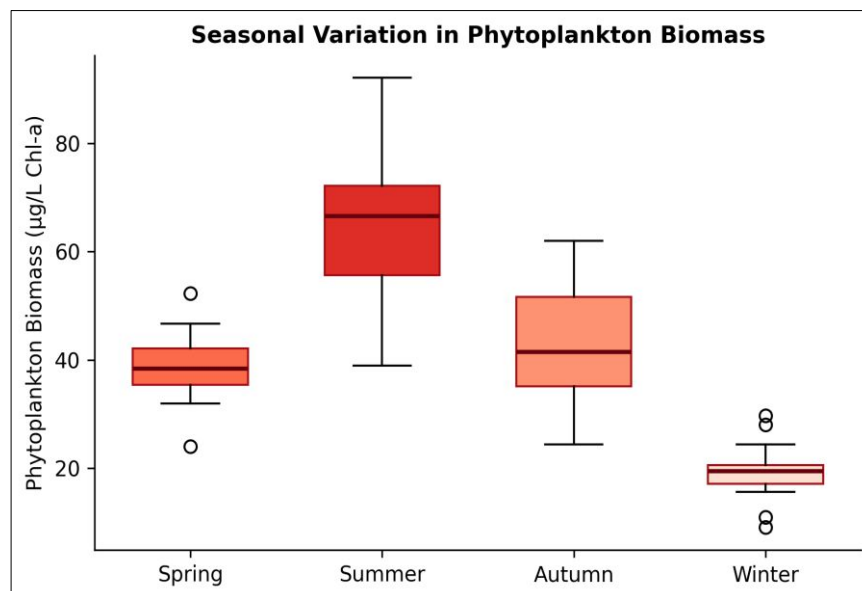


Fig 2: Box plots showing seasonal variation in phytoplankton biomass (chlorophyll-a) at five stations in Lake Izumi. Boxes show interquartile range; horizontal lines indicate medians

Comprehensive interpretation

The strong overall correlation between chlorophyll-a and primary productivity ($R^2 = 0.83$; Figure 1) confirms that biomass is a reliable proxy for carbon fixation in this system. However, the scatter around the regression line was wider in summer than in other seasons, likely because cyanobacterial buoyancy regulation concentrates cells near the surface, creating vertical heterogeneity that the

integrated sampling approach partly smoothed. Stepwise regression with season as a blocking factor retained water temperature and SRP as the best two-predictor model for annual biomass (adjusted $R^2 = 0.76$, $p < 0.001$). When spring data were analysed separately, DIN replaced SRP as the second predictor alongside temperature, reinforcing the seasonal shift in nutrient limitation.

Discussion

The seasonal biomass pattern in Lake Izumi follows the broad template described for shallow eutrophic lakes in the temperate zone, with spring diatom growth giving way to summer cyanobacterial dominance^[3]. But peak chlorophyll-a values (73.2 µg/L) exceeded those reported for comparable Japanese lakes such as Lake Kasumigaura (55–65 µg/L), suggesting that the combination of wastewater inputs and a small, warm catchment pushes Lake Izumi toward the extreme end of the eutrophication spectrum^[4]. The seasonal switch in the identity of the limiting nutrient nitrogen in spring, phosphorus in summer has practical implications for management. Single-nutrient reduction strategies, which historically focused on phosphorus alone, may fail to control spring diatom blooms if DIN remains high^[9]. Dual-nutrient management, targeting both N and P, appears more appropriate for this lake, a conclusion consistent with recent recommendations for shallow hypereutrophic systems in East Asia^[13]. Cyanobacterial dominance during summer coincided with water temperatures above 28 °C, a threshold that favours *Microcystis* over competing taxa due to its ability to regulate buoyancy and access surface light even in turbid water^[7]. Climate projections for the Osaka region suggest that the number of days exceeding 28 °C will increase by two to three weeks by mid-century, which could extend the cyanobacterial bloom window and worsen microcystin risk^[14]. The secondary autumn diatom pulse is less commonly reported in Japanese lakes and may reflect a nutrient release event during autumn turnover, when sediment-bound phosphorus re-enters the water column in shallow, wind-exposed basins^[10].

Conclusion

This 12-month survey of Lake Izumi revealed a pronounced seasonal cycle in phytoplankton biomass and primary productivity, with summer chlorophyll-a values roughly four times those of winter and carbon-fixation rates peaking above 140 mgC/m³/day during the August cyanobacterial bloom. Diatoms dominated the spring assemblage, cyanobacteria controlled the summer, and a mixed chlorophyte-diatom community characterised autumn, while winter was marked by low biomass and cryptophyte prevalence. The identity of the nutrient most closely tied to biomass shifted from dissolved inorganic nitrogen in spring to soluble reactive phosphorus in summer, indicating that single-nutrient management strategies are unlikely to control blooms year-round. Dual-nutrient reduction targeting both nitrogen and phosphorus inputs particularly from the municipal wastewater discharge offers the most promising path toward lowering peak biomass and associated microcystin risk.

Chlorophyll-a proved a reliable predictor of primary productivity ($R^2 = 0.83$), which simplifies monitoring because chlorophyll measurements are faster and cheaper than bottle incubations. Future work should extend the monitoring programme to multiple years to capture interannual variability, incorporate high-frequency sensor data for finer temporal resolution, and link phytoplankton dynamics to zooplankton grazing pressure, which was not measured here but is known to influence clear-water phases in shallow lakes. Given the projected warming of the Osaka region, tracking changes in the duration and intensity of the summer cyanobacterial bloom window is especially urgent.

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Contributions not qualifying for authorship

Ms. Yuki Harada assisted with phytoplankton identification during the summer sampling period, and Mr. Daiki Mori helped maintain the field instrumentation.

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