Photosynthesis-Irradiance Relationship and Primary Production of Phytoplankton in Lake Gocheonam

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Abstract - Photosynthetic activities and primary production of phytoplankton were investigated in Lake Gocheonam from October 1999 to August 2000. As an estuary lake with a barrage in the Southwestern coast of the Korean peninsula, the lake has received more attention after it became known as the habitat of large population of rare and endangered bird-Baikal Teal. As the lake had high algal biomass ranging from 20 μg chl-*a* L^{-1} to 125 μg chl-*a* L^{-1} in average values and rich eutrophication indicator species, the freshwaters were in a very productive or hypertrophic state. In the results obtained from the phytoplankton incubation in the laboratory, the maximum photosynthetic rate (P_{max}) varied according to seasons and sampling stations. Photosynthetic activities were higher during the warm season than the cold seasons and the serial order of P_{max} was August dominated with *Microcystis*, April with *Chlamydomonas* and *Nitzschia*, October with *Chlamydomonas* and January with *Stephanodiscus*. The water of the lake was persistently turbid throughout the year due to strong winds from the adjacent sea. Despite the water turbidity, the phytoplankton productions estimated from a mathematical model had very broad range from 18 mg C m^{-2} day^{-1} to 10,300 mg C m^{-2} day^{-1}.

Key words : phytoplankton, P-I curves, P_{max}, I_k, primary production, turbid water

INTRODUCTION

Understanding a variety of factors that control the primary production of phytoplankton is a fundamental theme in aquatic ecology. Primary production in aquatic systems is regulated by both biotic (trophic interaction including herbivory and predation) and abiotic mechanisms (nutrient fluxes and physical variability). In freshwaters, nutrients are a key factor for the growth and production of phytoplankton. The nutrient status in the euphotic zone depends upon nutrients loads from external surroundings or vertical water column fluxes.

Allthough streams and rivers are characterized by a continuum gradient of the flow, an estuary lake such as Gocheonam traps nutrients and organic materials from upstream. And these high concentrations of organic matters in the lentic waters could support large population of organisms and microbial assemblages. The receiving waters from two rivers-the Haenam Stream and the Samsan Stream-became a lake with the construction of a barrage in 1994 (Fig. 1). Lake Gocheonam has received more attention after it became known as the habitat of rare and endangered speciesof birds-especially the large population of Baikal Teal (*Ana formosa* Georgi) (Lee and Kang 2000).

With the gradual increase of eutrophication in the inland freshwaters, primary productions of phytoplank-

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ton have become topics in the freshwater ecology in Korea. Algal productions were studied in estuary freshwaters of Naktong River (Lee 1994; Cho *et al.* 1995; Jeon and Cho 2004), Yeongsan River (Choi 1988), Han River (Namkung *et al.* 2001), Lake Soyang (Namkung *et al.* 2001) and other freshwaters. The objectives of this study are to determine the seasonal patterns of primary production and photosynthetic efficiency of the phytoplankton. The study also carried out an evaluation of the eutrophication process after the construction of a barrage.

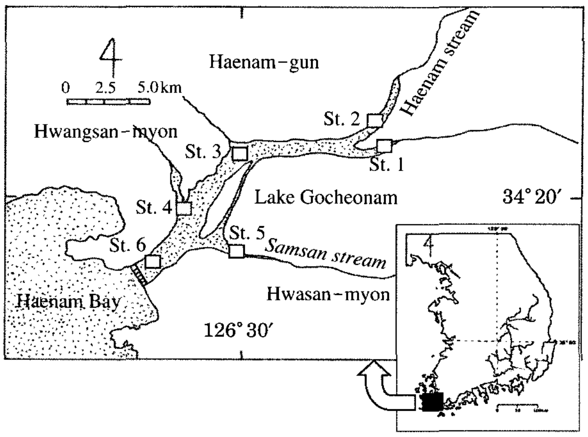

Fig. 1. Map showing the lake geography and sampling stations for the phytoplankton production in Lake Gocheonam. The lake and its surroundings were a habitat of the importantly migratory birds.

SITE DESCRIPTION

Lake Gocheonam (34° 20′-34° 35′N, 126° 25′-126° 40′E) is in contact with Haenam Bay located at the southwestern coast of the Korean peninsula (Fig. 1). With the objectives of providing water resource for agriculture, from 1985 to 1994, an artificial lake was created after the construction of a barrage at the mouth of the river. The lake is 6.4 km long and 1.2 km wide, and the water depth along the channel in the lower parts of the lake is from 0.3 m to 5.6 m. The total water capacity of the lake amounts to 1.50×10^6 m^3 and the available water resource was approximately 0.97×10^6 m^3. The drainage basin of the lake is typically composed of agricultural land of 18.1 km^2. The salinity of the surface water during the dry season ranged from 1.8‰ to 4.3‰ throughout the entire region of the lake (Im and Kim 2000). The sediment, which is primarily composed of clay and silt along the 15-20 m depths, is not entirely desalinized after the construction of the barrage. There were no significant salinity differences between the surface and the bottom of the lake due to the turbulence created by strong winds. And, the relatively open shoreline of the lake is highly susceptible to wind blowing from the sea.

The lake was very productive and hydrophytes were abundant in it. Emergent plants such as *Phragmites australis* (Cav.) Trin. ex Stend. and *Typha orientalis* Presl. were well developed around the lake periphery, and submerged or floating-leaf macrophytes such as *Trapa japonica* Flerov. and *Hydrilla verticillata* Casp. were abundant along the marginal zone of the lake (Im and Kim 2000). Along the eastern parts of the lake, a large island of natural wetland was covered with *Phragmites australis* and *Typha orientalis*. The wetland was approximately 3 km long and 0.4-1 km wide. It had surface area depending on the variable water level of the lake.

After the construction of the barrage, the lake and its surroundings became the major habitat of migratory birds in the southwestern region of the Korean peninsula. Especially, it is currently the largest wintering site for the Baikal Teal-a threatened species. The population size of Baikal Teal in Lake Gochenoam is 200,000 individuals from January to February and it is the largest population in the world (Lee and Kang 2000). Because of such worldly importance, the conservation of Lake Gocheonam has been under consideration in the Ministry of Environment of Korea.

MATERIALS AND METHODS

Sampling and experiments for the phytoplankton production were conducted at four times-October 20 in 1999, January 26, April 7, August 3 in 2000. Two liters of surface water were collected with a Van Dorn sampler and one liter water was used to measure the photosynthesis and the chlorophyll *a* extraction, and the remaining water was fixed with Lugol solution for the phytoplankton observation. When river waters were collected, water temperature, pH, DO and underwater irradiance were measured in field. The photosynthetic activity of the phytoplankton was measured with the ^{14}C isotope method in laboratory conditions. Exact 1.0 μCi of $NaH^{14}CO_3$ solution was spiked into three light bottles and a dark bottle containing 25 mL of lake water. The water samples were maintained in the algal culture room at the incubation temperature simulating the ambient temperature of the lake water. The bottles were incubated under the fluorescent light for 3 hours, under maximum irradiance of 400 μmol m^{-2} s^{-1}. Photosynthetic active radiation (PAR) was measured with a quantum sensor (Li-Cor 192SB, Li-Cor 190SA) and data logger (Li-Cor 1000). After laboratory incubation, the samples were preserved with formalin and passed through membrane filters (Whatman, 0.1 μm, 25 mm). The filters were dissolved in a 5 mL scintillation cocktail solution to measure the 14C activity of the alga cells with a scintillation counter (Packard Tri-Carb 2000CA). The alkalinity was measured by the Gran titration method (Wetzel and Likens 1991) using a 0.1N HCl solution. For the determination of photosynthetic pigments, samples were filtered with glass fiber filters (Whatman GF/C, 0.45 μm, 47 mm) and the algal chlorophyll *a* concentration was determined as reported by Nusch (1980) using the ethanol boiling extraction.

Vollenweider (1965) calculation was used to estimate the total daily production of phytoplankton. Primary production is a function of the chlorophyll *a* concentration (N) and the specific photosynthesis (P). Photosynthesis (NP_{max}) multiplied by depth ($z_{0.5Im}$) that corresponds to half I_m irradiance approximately equals to the production of the vertical production ($\sum NP$) at a selected times of a day. I_m is the light-saturated irradiance from the P-I curve. $z_{0.5Im}$ is related to the irradiance immediately beneath the surface (I'_0) through the vertical extinction coefficient (ε) as followed,

$$z_{0.5}I_m = \ln(I'_0/0.5I_k) \cdot \varepsilon^{-1}$$

$\sum NP$ the light-saturated photosynthesis (NP_{max}) as follow.

$$\sum NP = NP_{max} \cdot \ln(I'_0/0.5I_k) \cdot \varepsilon^{-1}$$

The daily integral phytoplankton production ($\sum\sum NP$, mg C m^{-2} day^{-1}) can be determined from the sequential profiles of $\sum NP$ at selected times through the day and day length. P_{max} accounted for the specific photosynthesis at 0.25 m depth and I_m was 2 times of I_k.

$$\sum\sum NP = [0.67-0.83]\, NP_{max} \cdot \Delta \cdot \ln([0.63-0.77]I'_0/\, 0.5I_k) \cdot \varepsilon^{-1}$$

RESULTS AND DISCUSSION

1. Flora and biomass of phytoplankton

The phytoplankton of the lake was dominated by a few important species and its species composition exhibited a clear seasonality. In January, *Stephanodiscus hantzschii* f. *tenuis* (Cl.) Bethge was a predominant alga to colonize the phytoplankton (Fig. 2). In April, *Nitzschia acicularis* (Kütz.) Kütz. bloomed in the upper region of the lake and *Chlamydomonas* sp. also showed similar biomass at the mouth of the agricultural channels. In August, *Microcystis aeruginosa* (Kütz.) Kütz. and

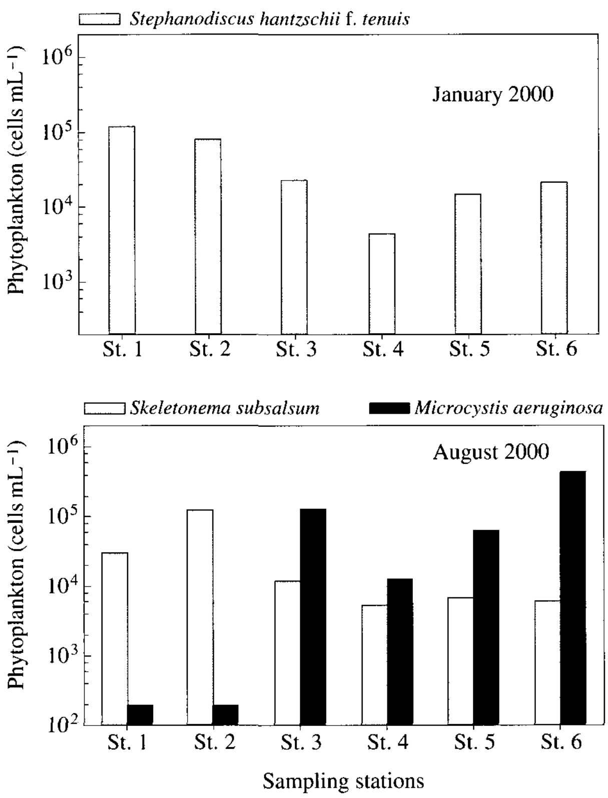

Fig. 2. Dominant species of the phytoplankton in Lake Gocheonam.

its relative cyanobacteria occurred in large numbers in the lower parts of the lake and whereas *Skeletonema subsalsum* (Cl.) Bethge was dominated throughout the lake (Fig. 2). In addition, *Microcystis wesenbergii* (Kom.) Kom. occurred with significant abundance in the upper regions. *Skeletonema subsalsum* of approximately 120,000 cells m L^{-1} were observed to change the color of lake water to brown during the algal bloom periods. The abundance of phytoplankton was very low in October and *Chlamydomonas angulosa* Dill. occured within the very turbid water.

Diatoms and chlorophyte algae dominated the phytoplankton of Lake Gocheonam over 70% of the standing crops throughout the sampling periods. The species composition of phytoplankton in the lake corresponded to the eutrophic algal affiliations such as *Microcystis aeruginosa* and *Stephanodiscus hantzschii* f. *tenuis*. Another feature of the phytoplankton of the lake was that there were more standing crops during the summer and winter than in the spring and autumn. In addition, there were large blooms of two diatom species-*Nitzschia acicularis* and *Skeletonema subsalsum*. Large blooms of there algal groups have not been reported in Korean freshwaters.

In the present study, the phytoplankton biomass was estimated with chlorophyll *a* concentration (Fig. 3). The chlorophyll *a* concentrations of the surface water samples were highly variable depending on the season or sampling stations. It ranged from 5 $\mu g\ L^{-1}$ in October to 194 $\mu g\ L^{-1}$ in August and its average was 92 $\mu g\ L^{-1}$ throughout the year. The Station 2, which is located at the main stream of the lake, showed pronounced peaks in phytoplankton biomass. In the Station 2, except for the month of October, chlorophyll *a* concentration ranged from 177 $\mu g\ L^{-1}$ to 194 $\mu g\ L^{-1}$, while it fluctuated from 28 $\mu g\ L^{-1}$ to 72 $\mu g\ L^{-1}$ in the Station 5. Though the phytoplankton biomass showed irregular fluctuation throughout the stations, the mean chlorophyll *a* concentration in October of 1999, January, April and August of 2000 were 20 $\mu g\ L^{-1}$, 87 $\mu g\ L^{-1}$, 66 $\mu g\ L^{-1}$ and 125 $\mu g\ L^{-1}$, respectively. Despite that the drainage basin of the lake was a typical agricultural land, there were persistent blooms of phytoplankton in the lake.

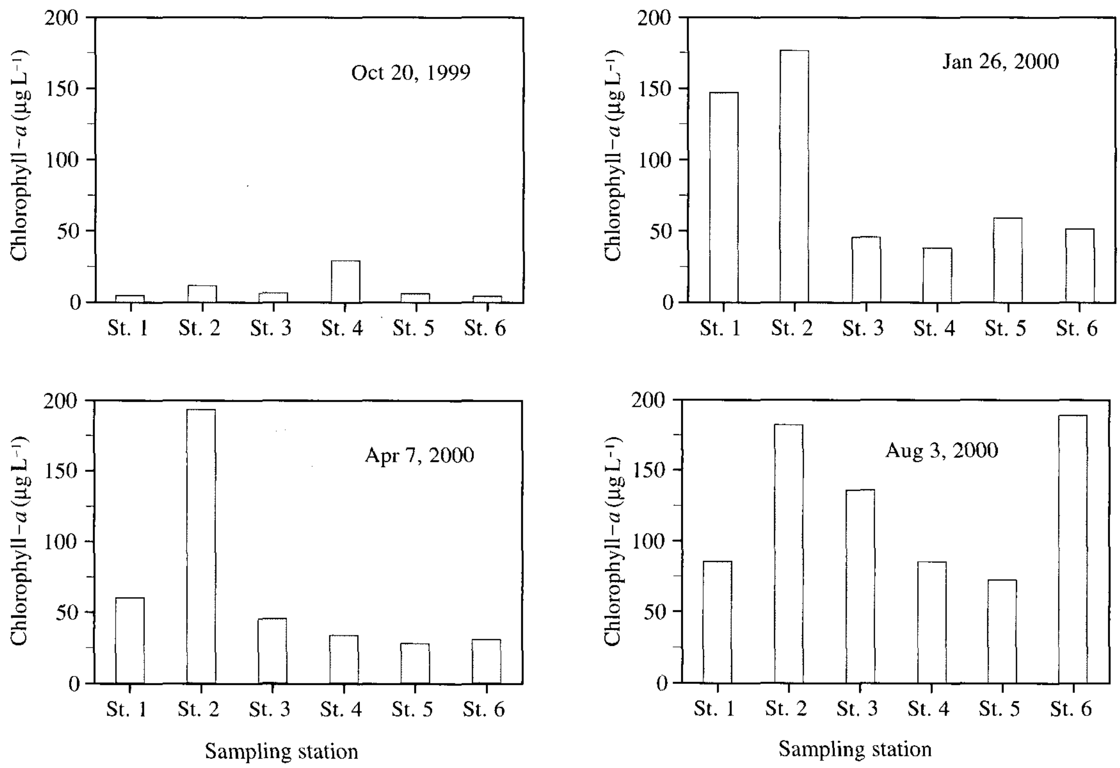

Fig. 3. Chlorophyll *a* concentration as the biomass of the phytoplankton in Lake Gocheonam through the season and sampling stations.

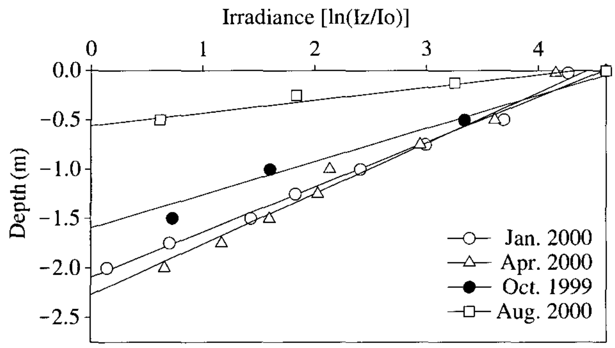

Fig. 4. The light penetration along the water depth and the euphotic depth in Lake Gocheonam. Light intensity at the surface (I_0)and the water depth (I_z).

2. Light

Light penetration through the water depth is presented in Fig. 4. The euphotic depth, at which light intensity falls to 1% of that at the surface, ranged from 0.6 m to 2.3 m. The extinction coefficient of light ranged from 2.0 m^{-1} to 7.8 m^{-1}. As active area for the photosynthesis of phytoplankton, the euphotic depths are important to regulate the photosynthetic activity and primary production of phytoplankton. This lake was exposed to strong winds blowing from the sea and had very rough wave throughout the year. It was assumed that the wind was sufficient to disturb the sediments in the shallow-depth area of the lake. As a consequence, significant turbid waters persisted in this lake. In October, the water of the lake was extremely turbid despite the low standing crops of phytoplankton. In the summer, the water turbidity was affected by phytoplankton bloom and suspended sediments resulting from the wind. Light penetration in the open water of the lake was determined by water color, the phytoplankton standing crops and the amount of suspended matters brought by wind-induced water circulation. Regardless of the turbid water environment, the lake supported high standing crops of phytoplankton.

3. Photosynthetic activity

The parameters of the phytoplankton measured under the laboratory light conditions, photosynthesis (P) and irradiance (I) based on chlorophyll *a* concentration and the water volume are presented in Fig. 5. Phytoplankton photosynthesis per unit water volume was high at the upper region (Station 2) during the sampling periods except in August. However, it was higher at the lower region (Station 6) in August (left figures of Fig. 5).

The specific photosynthesis and light adaptation of the phytoplankton were determined with maximum photosynthetic rate (P_{max}) and the half-saturation coefficient of irradiance (I_k) based on the unit chlorophyll *a* concentration. P_{max} and I_k were variable through the seasons and sampling stations (right figures of Fig. 5, Table 1). P_{max} and I_k ranged respectively from 0.8-7.6 mg C mg chl-a^{-1} hr^{-1} and 51-133 μmol m^{-2} s^{-1}. The maximum specific photosynthesis of the phytoplankton measured according to *in situ* techniques varied from 0.38 mg C mg chl-a^{-1} hr^{-1} to 11.25 μg C mg chl-*a* hr^{-1} (Harris 1978). P_{max} of phytoplankton primarily depended upon the dominant species. In August, the dominant species were *Skeletonema* (Station 2) vs *Microcystis* (Station 6), and in October, it was *Chalmydomonas* (Station 3) vs some diatoms (Station 6). P_{max} was at its lowest point in January and the P_{max} of cyanobateria and chlorophyte algae were more higher than that of diatoms. Photosynthesis based chlorophyll *a* was higher in the warm season and the serial order of P_{max} were August dominated with cyanobacteria (*Microcystis*)> April with diatom (*Nitzschia*) and chlorophyte (*Chlamydomonas*)> October with chlorophyte (*Chlamydomonas*)> January with diatom (*Stephanodiscus* and *Nitzschia*). The dependence of phytoplankton photosynthesis on the dominant species was frequently reported by authors (Cho *et al.* 1995; Han *et al.* 1999; Jeon and Cho 2004). The initial slopes of the P-I curves, namely P_{max}/I_k ratios, are a direct measure of light adsorption and the maximum efficiency of photosynthesis at low irradiance (Harris 1978).

In addition of the laboratory incubation, photosynthesis along the water depth was measured *in situ* at Station 6 in January. P_{max} values at 0.5 m depth were 28.50 mg C m^{-3} hr^{-1} and 1.01 mg C mg chl-a^{-1} hr^{-1}. Different with the laboratory measurements, photosynthetic activity in field was inhibited at the water surface and 0.25 m depth. It decreased linearly below the 0.5 m depth. The photosynthetic rate per unit chlorophyll *a* was same with the values obtained from the laboratory

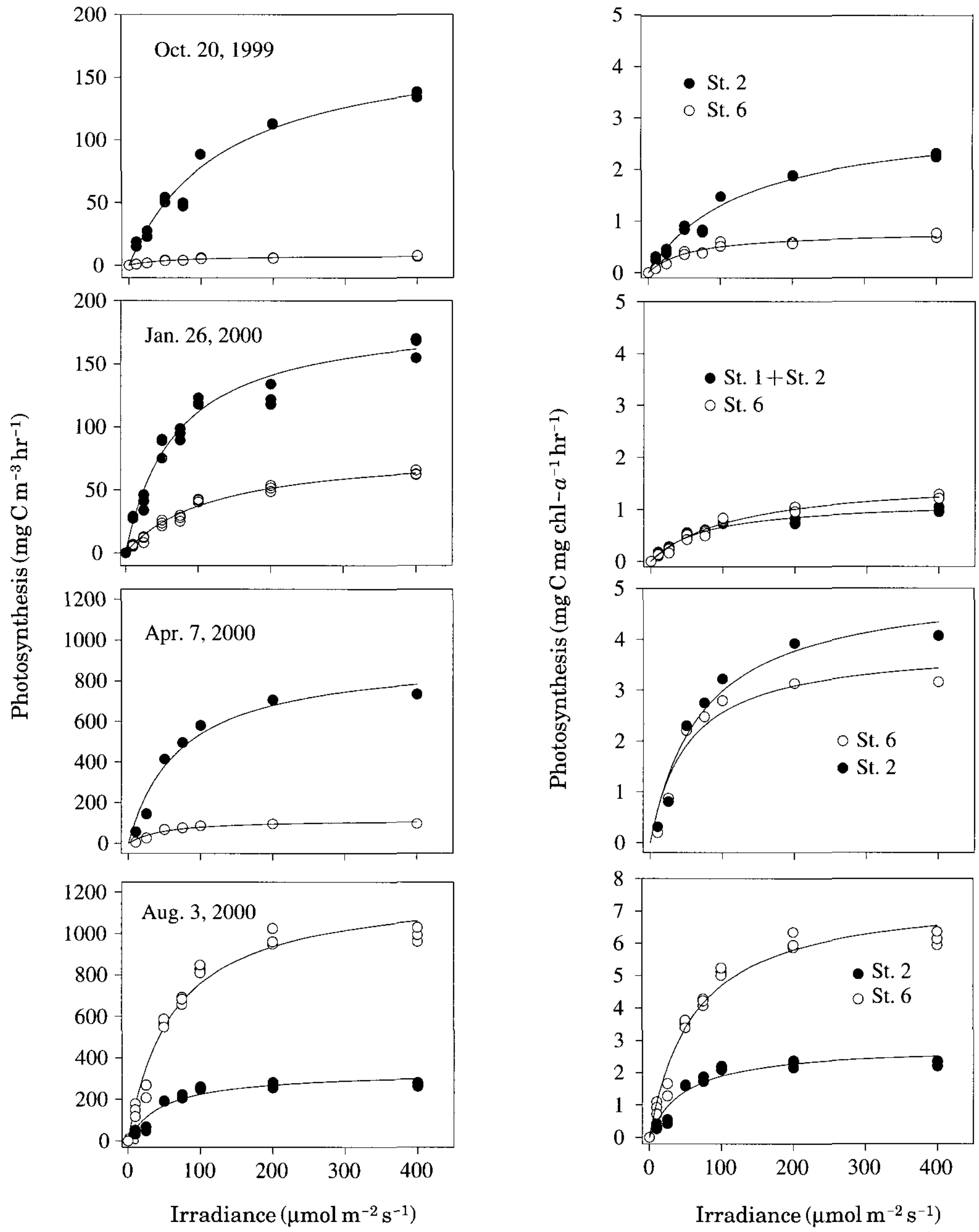

Fig. 5. Photosynthesis-irradiance (P-I curves) of the phytoplankton, which was incubated in the laboratory conditions, collected in Lake Gocheonam from October 1999 to August 2000. Photosynthesis per unit water volume (m^3) (left figures) and per unit chlorophyll a concentration (mg) (right figures).

incubation.

4. Daily primary production

To determine the daily production, the relationships of the specific photosynthesis (P) with the water depth (z) were recomposed using the P-I curves of Fig. 5 and the light penetration of Fig. 4. As a results from the Vollenweider (1965) methods to estimate the daily production of phytoplankton, daily production ranged from 18 mg C m^{-2} day^{-1} to 10,300 mg C m^{-2} day^{-1} (Table 2). Daily productions in Lake Gocheonam fluctuated with the seasons. It was lowest in October and highest in April. In August, it was estimated to be a mere 16% of that in April despite the same biomass of phyto-

Table 1. Parameters of P-I curves of the phytoplankton collected in Lake Gocheonam. P_{max}: maximum specific photosynthesis, I_k: half coefficient for light, α: photoadaptation

Month	Sampling stations	Incubation temperature (°C)	P_{max} (mg C mg chl-a^{-1} kr^{-1})	I_k (μmol m^{-2} s^{-1})	α (P_{max}/I_k)	Dominant algae
Oct. 1999	St. 2	20	3.03	133	0.023	*Chlamydomonas angulosa*
	St. 6		0.80	59	0.014	and its relatives
Jan. 2000	St. 2	7	1.61	120	0.013	*Stephanodiscus hantzschii*
	St. 6		1.17	77	0.015	f. *tenuis*
Apr. 2000	St. 1, 2	18	3.90	51	0.076	*Nitzschia acicularis* and
	St. 6		5.10	72	0.071	*Chlamydomonas species*
Aug. 2000	St. 2	25	2.82	49	0.058	*Skeletonema subsalsum*
	St. 6		7.57	62	0.122	*Microcystis aeruginosa*

Table 2. Daily primary production (mg C m^{-2} day^{-1}) of the phytoplankton of Lake Gocheonam

Sampling day/Station	Station 2	Station 6
Oct. 1999	43	18
Jan. 2000	3,760	790
Apr. 2000	10,300	3,500
Aug. 2000	1,610	4,180

plankton. Daily productions of the lake are higher than any other freshwaters in Korea. The ranges of primary production were 543-4,112 mg C m^{-2} day^{-1} in the estuary of the Nakdong River (Lee *et al.* 1994), 2,000-18,100 mg C m^{-2} day^{-1} in Seonakdong River (Jeon and Cho 2004), 250-2,000 mg C m^{-2} day^{-1} and 140-4,890 mg C m^{-2} day^{-1} in the estuary of Yeongsan River and Han River, respectively (Namkung *et al.* 2001).

The light-saturated photosynthesis (P_{max}) and the vertical extinction coefficient of light (ε) have the most influence in estimating the primary production. In this lake, the water turbidity and phytoplankton bloom were concomitant factors upon the primary production of phytoplankton. The high productions of phytoplankton supports the energy sources of the food webs and migratory birds would culminate in those biological webs.

ACKNOWLEDGEMENT

This work was carried out to contribute to the natural ecosystem investigation project supported by the Ministry of Environment of Korea from 1999 to 2000. The investigation presented here was designed to evaluate the lake and its surroundings as an important ecosystem, and to conserve the habitat of rare and endangered species-Baikal Teal and some migratory birds. We thank all for the support relevant to carry this research.

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