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Primary Productivity of Phytoplankton in the Shallow and Hypertrophic River (Seonakdong River)

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서낙동강에서 식물플랑크톤의 1차 생산성. 전승일 · 조경제* (인제대학교 낙동강환경연구센터)

서낙동강에서 ^{14}C법으로 1996년 1월부터 10월까지 식물플랑크톤의 1차 생산성을 측정하였다. 서낙동강은 수심이 얕고, 국내 호수와 하천 중에서 가장 수질오염이 심한 곳으로 진광층의 깊이는 1.4～2.1 m 범위였다. 식물플랑크톤의 chl-*a* 농도는 67～894 μg L^{-1} 범위였고, 8월에는 chl-*a* 농도가 크게 증가하였다. 최대 물질생산성은 수표면～0.4 m 깊이에서 나타났으며 2.1～4.3 mg C mg chl-a^{-1} hr^{-1} 범위였다. 광합성 (P)-광 (I)의 관계에서 식물플랑크톤의 광합성 저해는 높은 고광에서 현저히 저해되었으나 *Microcystis*가 대발생한 기간에는 광저해 현상이 나타나지 않았다. Chl-*a* 당 식물플랑크톤의 1차 생산성은 입사 광에너지의 양에 비례하였으며 면적 당 1차 생산성은 chl-*a* 현존량과 직선적으로 비례하여 식물플랑크톤의 1차 생산성은 결과적으로 생물량과 광의 함수였다. 과거 자료를 수집한 결과, 낙동강 하구 지역에서 식물플랑크톤의 생산성은 하구둑 건설 (1987년) 이후 해가 감에 따라 점진적으로 증가하여 이 지역의 부영양화 현상을 반영하였다. 식물플랑크톤의 연 생산성 개념에서 평균 10 μg chl-*a* L^{-1}의 생물량 증가는 30 mg C m^{-2} day^{-1}의 단위면적 당 생산성 증가를 가져왔다.

Key words : phytoplankton, primary productivity, eutrophication, photoinhibition

INTRODUCTION

A starting-point in the water system is the organic matter production through photosynthesis by autotrophic producers. The organic matters produced by phytoplanktons would be the forcing energy in the freshwater ecosystem and food sources for heterotrophic organisms. Such organic matters are considered as autochthonous as well as allochthonous matters from basins (Choi, 1994; Shin *et al*., 1996). In this sense, the primary productivity and photosynthetic activity have been a considerable interest in the ecology of phytoplankton. Once nutrients are provided from the surroundings in adequate supply to support the maximum photosynthesis, irradiance availability may be a dominant factor regulating the primary productivity (Harris, 1978). Actually, total productivity by phytoplankton can be primarily the function of the algal biomass and irradiance availability.

Estuarine area of the Nakdong River, which is composed of three rivers (Nakdong, Seonakdong and Joman River), had algal blooms after the construction of the river barrage. Phytoplankton have abundantly occurred throughout a year, and monospecific algae such as *Microcystis aeruginosa* and *Stephanodiscus hantzschii* f. *tenuis* have bloomed in summer and in cold seasons, respectively (Cho and Shin, 1998). It has been known that Seonakdong River is one of the most fertile waters in Korea as shown in high algal productivity (Kim *et al*., 1996). The Seonakdong River is a estuarine tributary of the Nakdong River and a river-like lake with watergates in

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the river mouth to protect the intrusion of saline water for the agricultural irrigation. Seonakdong River passes through the agricultural delta plains and rice field. The agricultural waters have been pumped from the Seonakdong River and the most irrigated waters drained into the Joman River. Diverse pollution sources such as cities and industrial zone are scattered around the river. The productivity of phytoplankton was measured at the vicinity of Gimhae Bridge in the upper zone of the river.

As productive waters with high cultural eutrophication, the primary production in the Nakdong River has been an important theme for the freshwater ecology. The study on the algal flora and primary production of phytoplankton were already conducted in the past for the environmental impact assessment (EIA) on the estuarine barrage construction and civil works (Hong *et al.*, 1984, 1985, 1986, 1987). After then, phytoplankton production was carried out to evaluate the eutrophication trend after the construction (Lee *et al.*, 1994; Cho *et al.*, 1995) and to assess the allochthonous contribution of organic matter produced by phytoplankton (Choi, 1994). The overall objective of this research was to determine the photosynthetic activity and primary production of phytoplankton in the Seonakdong River, and some patterns of the primary production in the estuarine freshwaters of the Nakdong River.

MATERIALS AND METHODS

Four liter water was collected from the selected depth using a Van Dorn sampler. The half water was used to measure production and chlorophyll-*a* concentrations and the other half to observe phytoplankton under microscope. Water temperature, pH, DO and underwater irradiance were measured in field when river water was collected to conduct ^{14}C isotope methods. $NaH^{14}CO_3$ solution of 1 mL was spiked into 50 mL river water of 3 light and 1 dark bottle. The bottles were incubated at the corresponding depth (surface, 0.1 m, 0.2 m, 0.4 m, 0.6 m, 0.8 m, 1.0 m and 1.5 m) during 3 hours (11:00~14:00). After *in situ* incubation, materials were preserved with formalin and passed into membrane filters. The filters were dissolved in 5 mL scintillation cocktail solution to measure the ^{14}C activity of algal cells with scintillation counter (Packard Tri-Carb 2000CA). In addition, photosynthesis of natural and cultured *Microcystis aeruginosa* was measured by oxygen method using oxygen monitor (CBI-D) in addition to the ^{14}C isotope measurements.

Aerial and underwater irradiance (PAR, photosynthetic active radiation) were continuously monitored with quantum sensor (Li-Cor 192SB, Li-Cor 190SA), recorder (Yokogawa 3057) and data logger (Li-Cor 1000) during the measurement. Alkalinity was measured by Gran titration method (Wetzel and Likens, 1991) using 0.1 N HCl solution. Phytoplankton chlorophyll-*a* concentrations were determined with the ethanol boiling extraction of Nusch (1980).

RESULTS AND DISCUSSION

Six measurements were conducted at the upper region of the Seonakdong River in 1996. Environmental parameters of the river water are presented in Table 1. Dissolved oxygen (DO) of the surface water had 120~270% saturation range to show the hypersaturation, while hypoxic conditions below 2.0 mg L^{-1} were kept in the bottom waters in January and August. Alkalinity ranged from 94 mg L^{-1} to 171 mg L^{-1} throughout the season. Incident irradiance at 1.5 m depth ranged from 3% to 5% of the surface irradiance. The penetration depth of irradiance was very shallow in the time of *Microcystis* blooming in August to reach 6% of surface irradiance at 0.5 m depth.

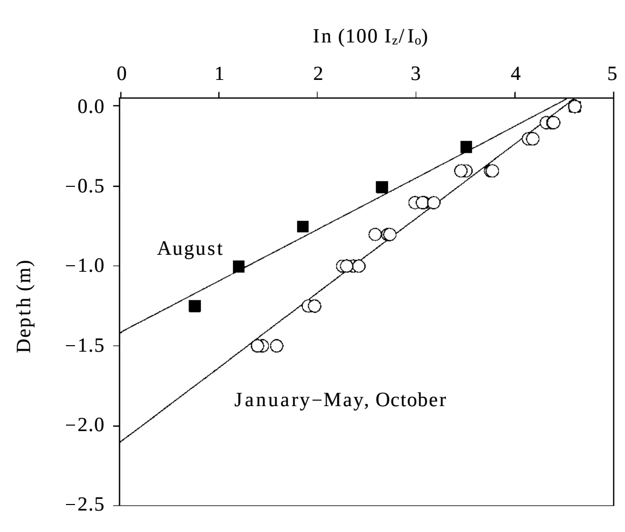

Fig. 1. Irradiance under the water and euphotic depth. I_0 and I_z refer to irradiance of surface and corresponding depth (z), respectively.

Table 1. Water temperature (°C), pH, alkalinity (mg $CaCO_3$ L^{-1}), DO (mg O_2 L^{-1}), conductivity (mS cm^{-1}) and extinction coefficients (k m^{-1}) of irradiance in the Seonakdong River, 1996.

Date＼Item ＼Depth (m)	Temperature		pH		Alkalinity		DO		Conductivity	k
	0	1.0	0	1.0	0	1.0	0	1.0		
Jan. 12	3.6	4.3	8.6	7.4	148	109	16.2	3.0	1.07	2.0
Mar. 12	6.9	6.9	7.8	7.9	127	132	14.8	14.0	1.14	2.0
Mar. 26	9.4	9.3	7.9	8.0	155	159	16.8	15.5	1.04	2.2
May 9	19.2	19.0	7.7	8.4	160	158	13.2	12.6	1.03	2.3
Aug. 2	32.3	30.1	8.8	7.8	171	155	19.7	1.5	0.65	3.9
Oct. 16	19.9	18.3	8.6	8.2	94	96	12.1	11.8	–	3.0

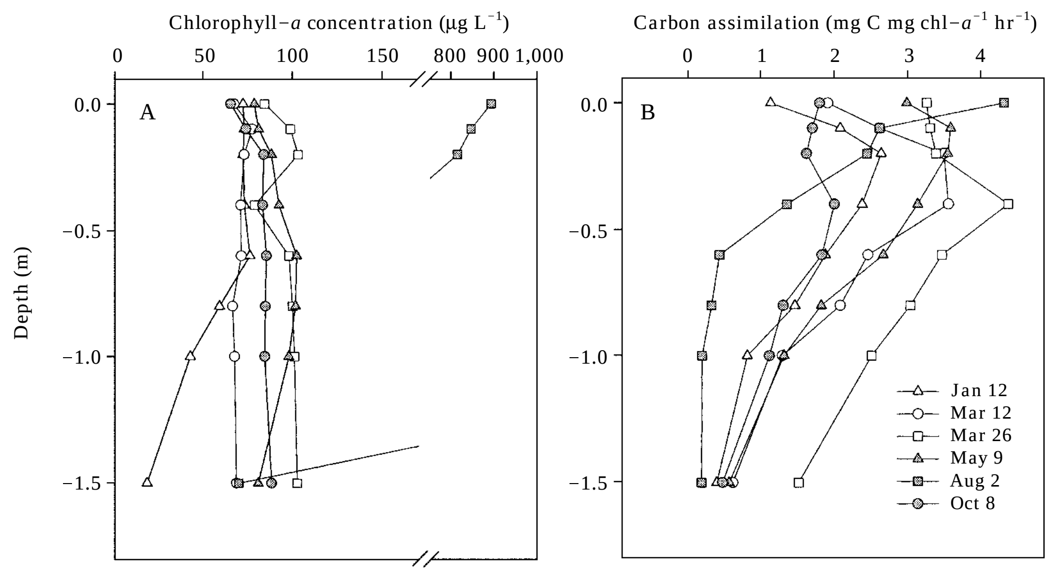

Fig. 2. Depth profiles of chlorophyll−*a* concentrations (A) and *in situ* primary productivity per unit chlorophyll−*a* and for an hour (B) in 1996.

Euphotic depth was 1.4 m in August and 2.1 m in the remaining season except August (Fig. 1).

Diatom *Stephanodiscus hatzschii* f. *tenuis* and its relatives predominated over the lower parts of the Nakdong and Seonakdong River from January to March, and cryptomonad *Rhodomonas minuta* partially bloomed with *Stephanodiscus* diatoms in late March. Chlorophycean algae gradually increased after May and other diatom flora succeeded *Stephanonodiscus* species. Filamentous diatoms such as *Aulacoseira ambigua* and *A. granulata* etc, and chlorophyceans occurred in May and October and diverse algal species or assemblages constituted the phytoplankton to have the highest diversity in a year. In August after the rainy season, *Microcystis* and other cyanobacteria explosively bloomed and occasionally made floating scums on the surface water. Algal blooms were observed in winter and summer as *Stephanodiscus* persistent blooms in cold season and *Micrcocystis* outbreaks in the warm season in 1996.

The variations of chlorophyll−*a* along the water depth profile were presented in Fig. 2A. Surface chlorophyll−*a* concentration ranged from 67 µg L^{-1} to 85 µg L^{-1} except the data of August. The concentration in August was 894 µg L^{-1}. Phytoplankton biomass was kept within a constant range through the season except August. Although distribution of chlorophyll−*a* along the depth profiles showed little variations, chlorophyll−*a* increase was observed in the middle depth (from 79 µg L^{-1} at surface to 102 µg L^{-1} at 06∼0.8 m depth) in May and significant decrease was detected in the bottom waters in January and August.

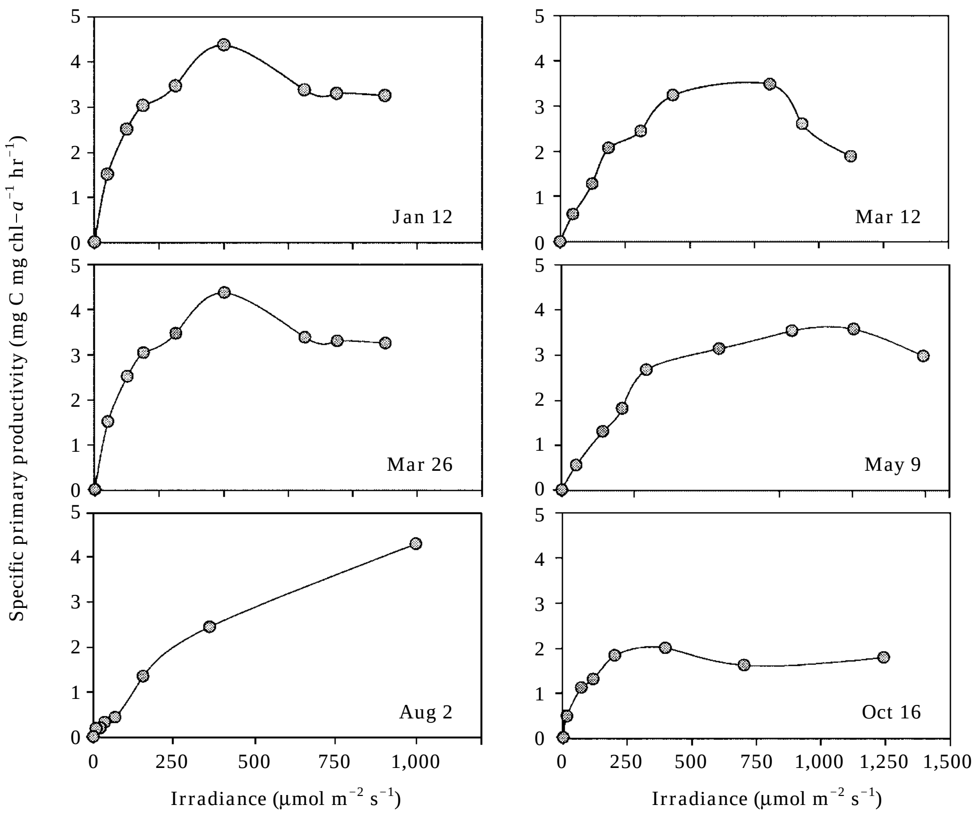

Fig. 3. Productivity (P)-irradiance (I) curves and photosynthetic photoinhibition of phytoplankton in the Seonakdong River in 1996.

Measurements of photosynthesis in the closed bottles, which were exposed at the depth in the water column, showed consistently generalized patterns to depict primary productivity (P)- depth (D) curves. Fig. 2 showed typical patterns of depth profiles in relation to irradiance penetration and algal biomass. In the P-D curves, three components-light-limited zone of the bottom parts of the curves, light-saturation or maximum photosynthesis (P_{max}) and light-inhibition zone of photosynthesis depression near the surface-are recognizable. Specific productivity at surface was 1.1~4.3 mg C mg chl-a^{-1} hr^{-1} range and P_{max} in the P-D curves ranged from 2.1 mg C mg chl-a^{-1} hr^{-1} to 4.4 mg C mg chl-a^{-1} hr^{-1}. P_{max} occurred 0.1~0.4 m depth except August, while P_{max} in August was observed in the most upper surface to show no photosynthetic inhibition. As this measurements were carried out in the middle parts of a day under cloudless day, interference with irradiance was excluded.

Productivity-depth profiles of Fig. 2B were transformed to productivity-irradiance (P-I) curves as Fig. 3. Algal photosynthetic inhibition occurred from 400 μmol m^{-2} s^{-1} to 1,000 μmol m^{-2} s^{-1} irradiance. Photoinhibition was evident during the periods when diatom *Stephanodiscus* was predominated, while cyanobacteria *Microcystis* did not show the photoinhibition. Photosynthetic inhibition was not clear in May and October when chlorophyceans and diatoms *Aulacoseira* are dominant.

Photosynthetic activity using the natural assemblages and unialgal cultures of *Microcystis aeruginosa* collected from the Seonakdong River was measured under the controlled temperature and irradiance in the laboratory to clarify algal photoinhibition and P-I relationship (Fig. 4). In contrast to inhibition of cultured *M. aeruginosa* above 400 μmol m^{-2} s^{-1}, natural *Microcystis* assemlages did not show any photoinhibition and showed gradual increases of photosynthesis with the increase of irradiance (fluorescence lamp). The adaptation of *Microcystis* to low and high irradiance could be classified into two types by P-I curves of laboratory incubation. Unialgal *M.*

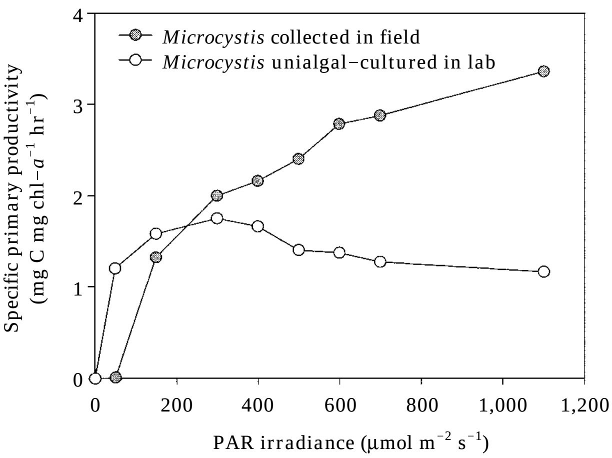

Fig. 4. P-I curves and productivity of *Microcystis aeruginosa* collected in field and cultured in laboratory.

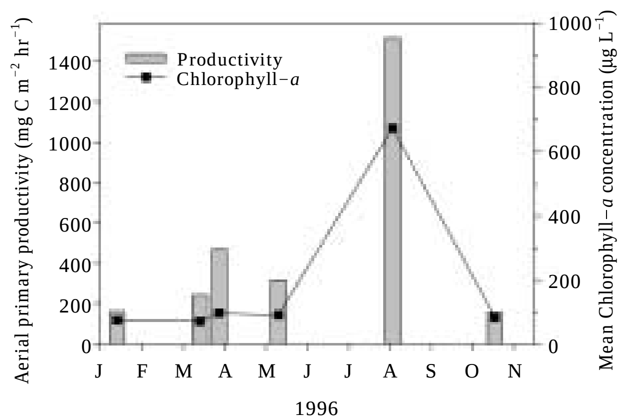

Fig. 5. Seasonal variations of mean chlorophyll-*a* concentration and aerial production of phytoplankton in the Seonakdong River.

aeruginosa cultured in laboratory adapted well to the low irradiance, while natural *Microcystis* assemblages tolerated high irradance above 1,100 μmol m^{-2} s^{-1}. Photoinhibition of natural phytoplankton has long been a well known phenomenon which has been observed in both freshwaters and marine waters over the world, and usually occurred above 200 μmol m^{-2} s^{-1} irradiance (Harris, 1978). The prominent factor is known to be ultraviolet radiations, which have directly effect on the photochemical reaction of photosynthesis and organic structures of cells (Reynolds, 1984). The mechanisms are not well at all understood in despite of the clear photoinhibition in algal photosynthesis.

Photosynthesis of phytoplankton may be influenced by other factors such as temperature, carbon source and nutrient supply. Specific productivity showed little variations through the season, considering 1.8~2.3 of the temperature quotient (Q_{10}) range (Harris, 1978) and wide range of ambient water temperature (from 3.6~32.3°C) (Fig. 3). Productivity data along the depth profiles were integrated to determine the aerial primary production of water column (Fig. 5). Aerial phytoplanktonic productivity except in August (1,518 mg C m^{-2} hr^{-1}) were from 155 mg C m^{-2} hr^{-1} to 470 mg C m^{-2} hr^{-1} to show narrow range.

Daily primary productions were determined from P-I curves of Fig. 3 and chlorophyll-*a* concentration profile. Daily productions in January, March, May, August and October were 2.3 g C m^{-2} day^{-1}, 2.3~6.9 g C m^{-2} day^{-1}, 10.0 g C m^{-2} day^{-1}, 18.1 g C m^{-2} day^{-1} and 2.0 g C m^{-2} day^{-1}, respectively. Daily Production gradually increased from January to August. From the daily productions and their extrapolation, annual primary production as carbon assimilation was estimated in the upper area of the Seonakdong River. Annual primary production was estimated as 1,314 g C m^{-2} yr^{-1}.

Phytoplankton productions would primarily be under the influence of phytoplankton standing crops, irradiance and nutrient availability. In our study, specific productivity were linearly correlated with total irradiance received during the measurement in field (Fig. 6A). Primary productivity of phytoplankton could be estimated from the function of irradiance intensity and chlorophyll-*a* standing crops. However, in the long-term records of primary productivity, limitation of biologically available phosphorus has been the major factor responsible for increase of both primary productivity and phytoplankton (Berman *et al.*, 1995). Over the world, variables related to solar energy have a greater influence on production than ones related to nutrient factors (Brylinsky and Mann, 1973).

Primary production data measured by ^{14}C method in the past were collected to clarify the eutrophication trend in this freshwater zone (Fig. 6B). Daily productions were intuitively determined by using the specific productivity, chlorophyll-*a* concentration and day length, and by successive integration of depth assimilation profile. Primary production of phytoplankton has

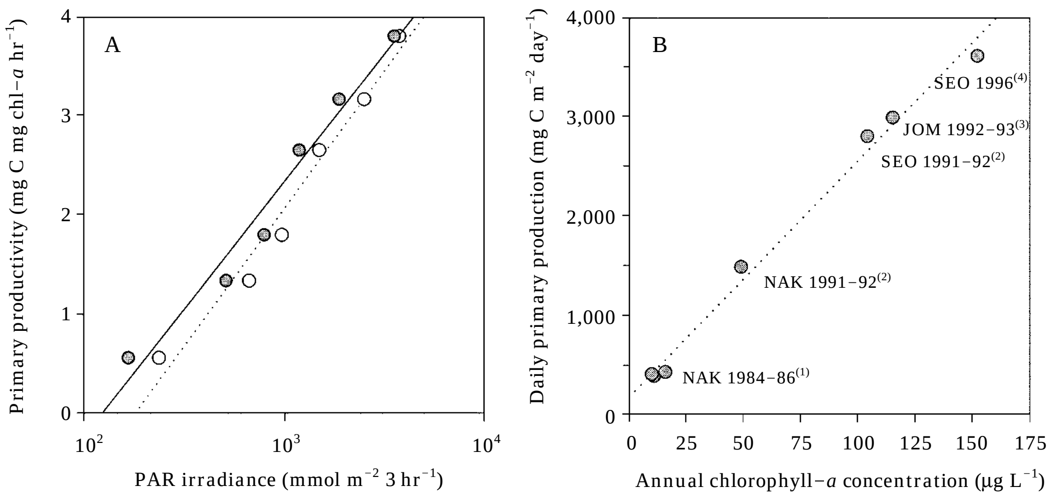

Fig. 6. Primary production as a linear function of total received irradiance (A) and interannual trends of phytoplankton production in the freshwaters of the Nakdong River Estuary (B). NAK: Nakdong River, SEO: Seonakdong River, JOM: Joman River. (1) Hong *et al.*, 1984, 1985, 1986, 1987, (2) Lee *et al.*, 1994, (3) Cho *et al.*, 1995, (4) The present study.

been measured from 1984 in the estuary of the Nakdong River for the environmental and ecological assessment. Cultural eutrophication showed a linear increase after the construction of estuarine dams (Fig. 6B). Chlorophyll-*a* concentration absolutely reflects the phytoplankton production and average 10 µg chl-*a* L^{-1} increase corresponded to phytoplanktonic production acceleration of 30 mg C m^{-2} day^{-1}. Primary productivity of phytoplankton in this freshwaters may play roles to guide and actually circumscribe the extent of the energy flow and food chain in the ecosystem as a source of the autochthonous organic matters. In spite of the shallow depth below 2.0 m, the growth of benthic algae on the bottom was completely inhibited with the highly turbid water in the Seonakdong River. A lot of the autochthonous organic matters in this river would be derived from the planktonic algae rather than the benthic algae. Autochthonous organic matters from phytoplankton accounted for 55% of total loads and their contribution was higher than the allochthonous origin in the Nakdong River (Choi, 1994). In addition, from the relationship between chlorophyll-*a* and BOD, percentage of autochthonous organic matter in total BOD exceeded 50% in the downstream of the Nakdong River (Shin *et al.*, 1996). As a result, the control of the phytoplankton growth or production would be the primary way to improve the water quality in this river.

ABSTRACT

Primary productivity of phytoplankton was measured by ^{14}C method from January to October of 1996 in Seonakdong River. This river was a highly productive freshwater showing the euphotic depth of 1.4 m in August and 2.1 m in the remaining season. Chlorophyll-*a* concentrations of phytoplankton ranged from 67 µg L^{-1} to 894 µg L^{-1} and showed the great increase in August. Maximum specific productivity was 2.1~4.3 mg C mg chl-a^{-1} hr^{-1} and occurred above 0.4 m depth. In photosynthesis-irradiance relation, photoinhibition or photosynthetic suppression of phytoplankton occurred clearly in the cold seasons, while phytoplankton (mainly *Microcystis aeruginosa* and its relatives) in August did not show any symptom of the photosynthetic inhibition against the high irradiance. The specific productivity of phytoplankton was eventually dependant upon incident irradiance to show the linear correlation with received irradiance in field, and the areal productivity of phytoplankton upon chlorophyll-*a* standing crops. In the downstream of the Nakdong River, phytoplankton productions have linearly increased since the estuarine barrage construction to reflect the gradual eutrophication in the estuarine area. Average chlorophyll-*a* increase of 10 µg chl-*a* L^{-1} absolutely corresponded to the primary produc-

tion acceleration of 30 mg C m^{-2} day^{-1} on the annual basis.

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