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Primary Production System in the Southern Waters of the East Sea, Korea
I. Biomass and Productivity

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한국 동해 남부해역의 일차생산계
I. 생물량과 생산력

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For the study on the structure and characteristics of the primary production system in the southern waters of the East Sea, chlorophyll, phytoplankton standing stocks, nutrients and hydrographic properties were investigated and analyzed in conjunction with measurement of C-14 based primary productivity. The primary productivity was relatively high in comparison with the previous studies, ranging from 284 to 4,574 $mgC \cdot m^{-2} \cdot day^{-1}$ and averaged to be 2,000 $mgC \cdot m^{-2} \cdot day^{-1}$. The standing stocks within the euphotic zone were fairly high, but ambient inorganic nitrogenous nutrient concentrations were too low to support the high production. This implied that there might be active recycling of nitrogenous nutrients by heterotrophic processes and the upward flux of nutrients by vertical mixing. Subsurface chlorophyll maxima were continuously observed in the lower parts of the euphotic layer and the depth coincided with the nutricline rather than isopycnal surfaces, supporting the view that chlorophyll distributions and primary production were primarily influenced by nutrient supply. Despite low nutrient concentrations, phytoplankton standing stocks and production were fairly high and the fraction of autotrophic nano- and picoplankton production was significant.

한국 동해 남부해역 일차생산계의 구조와 특성을 밝히기 위해 엽록소량, 식물플랑크톤 현존량, 영양염 및 수리적 성분들을 C-14 방법에 의한 일차생산력 측정과 병행하여 조사, 분석하였다. 그 결과 본 연구해역 일차생산력은 기존의 연구들에서 보다 높은 284 - 4,574 $mgC \cdot m^{-2} \cdot day^{-1}$의 범위로 측정되었으며 평균값은 2,000 $mgC \cdot m^{-2} \cdot day^{-1}$로 계산되었다. 진광대 내의 일차생산자 현존량은 비교적 컸으나 해수중 무기 질소태 영양염은 높은 일차생산을 유지시키기는 어려운 낮은 농도로 측정되었다. 따라서 질소태 영양염은 종속영양 생물과정과 수층의 수직혼합에 의한 상층으로의 유입에 의해 빠른 순환 공급이 예상된다. 표층하 엽록소량 최대 현상은 진광대의 기저부에서 계속적으로 관찰되었으며 그 깊이는 등밀도 표면대 보다는 영양염 약층과 더 밀접한 관계를 보여 엽록소량 분포와 일차생산이 일차적으로 영양염 공급에 영향받는 것으로 보인다. 따라서 본 연구해역은 낮은 영양염 농도에도 불구하고 식물플랑크톤 현존량과 생산량은 비교적 크고 자가영양 미소 및 초미소플랑크톤의 생산량이 중요하였다.

INTRODUCTION

The studies on primary production system have been investigated in various ocean environments, reporting many different results on phytoplankton distribution patterns. But most of them indicate that phytoplankton biomass is small at deep water. In general, phytoplankton requires sufficient solar radiation for photosynthesis, so that the communities are restricted within euphotic zone. In this respects, many researchers have reported vertical structures of phytoplankton communities in relation to the characteristics of water mass. One general feature of vertical structure is that phytoplankton is not most abundant in the surface water where light intensity is greatest, but abundant at subsurface level. Shim et al. (1991a) proposed two mechanisms on the formation of subsurface maximum. One is that the photosynthesis decrease and even may seriously inhibited at high light intensity. The other is that phytoplankton populations, especially diatoms, can't move independently so that tends to sink into the subsurface layer which corresponds roughly with the upper depth of thermocline. Therefore, subsurface chlorophyll maximum layers can be estabilished where light condition is good and water column is stratified.

Some studies on primary production system in this study area have been reported for the last few decades. Jun and Park (1969) discussed spatial variations of chlorophyll concentrations in relation to water temperature, inorganic phosphate concentration and transparency. Shim and Lee (1983) insisted that high primary production should be stimulated by the mixing of Tsushima Warm Current Water (TWCW), North Korean Cold Water (NKCW) and East Sea Proper Water (ESPW). Chin and Hong (1985) investigated primary production in the western channel of the Korean Strait and reported that chlorophyll concentration and productivity were high at surface water in autumn but low in summer. Cho (1985) measured micro and nanoplankton chlorophyll concentrations and Lee (1986) emphasized the significance of nanoplankton from the study on phytoplankton ecology in the East Sea. Kim (1988) discussed the relation between oceanic front and primary production and Park (1989) reported the forming mechanisms of chlorophyll maximum layer and vertical structure of phytoplankton communities. Shim et al. (1989) performed investigation in early spring and showed close correlation between phytoplankton communities and hydrographic conditions. The study area could be divided into three phytohydrographic regions: 1) East Korean Warm Water Region (a branch of Tsushima Current), 2) North Korean Cold Water Region, and 3) Offshore Water Region not affected by other two water regions. According to the results, N/P ratio was ca. 3 in surface layer, which indicated that nitrogen was the major limiting nutrient in this area. Chung et al. (1989) discussed primary productivity related to the dynamics of nitrogenous nutrient, concluding that the productivity and chlorophyll contents were relatively high in frontal waters where the NKCW met the East Korean Warm Water (EKWW). These studies imply the same result that nitrogenous nutrient is limiting factor to the growth of phytoplankton.

The purpose of this study is to discuss the primary production system related to hydrographic condition and to report the patterns of phytoplankton biomass and productivity in the southern waters of the East Sea.

THE STUDY AREA

This study area is located in the southwestern part of the East Sea (Sea of Japan) between 35°03′ - 37°47′N and 129°27′ - 133°04′E. The area overlies small marginal seas, continental shelf in the western and southeastern part, and is mostly characterized by continental slope and wide deep Ulleung Basin with a very flat bottom at a depth of more than 2,000 meters. Water masses of this study area are characterized by the three major water masses (Kim and Chung, 1982; Shuto, 1982); the Tsushima Warm Current Water (TWCW), the North Korean Cold Water (NKCW) and the East Sea Proper Water (ESPW). Later the existence of one more water mass, East Sea Intermediate Water (ESIW) of low salinity (<34.00‰) and high dissolved oxygen (>6.0 $ml \cdot l^{-1}$), was reported by Kim and Kim (1983). The warm water (TWCW) and the cold water masses (NKCW and ESPW) have shown various types of spatial distribution seasonally and annually (Lim and Chang, 1969; Lim, 1973; An, 1974; Hong and Cho, 1983; Kim and

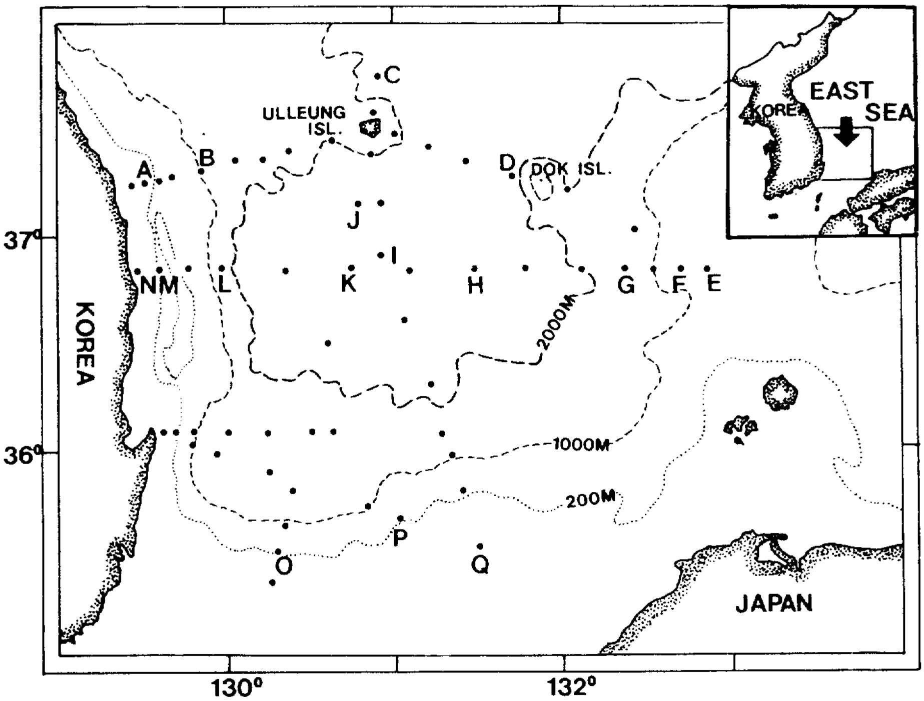

Fig. 1. The study area showing sampling stations.

Kim, 1983; Hong et al., 1984; Kim and Legeckis, 1986), which exerted major influence on not only hydrography but the distribution of plankton community (Lee, 1986; Kim, 1988).

Kim and Legeckis (1986) insisted that TWCW enter the sea through the Korea Strait, and flow northeast ward along the coast of Korea (East Korean Warm Water; EKWW). The current entered the East Sea flows northeast ward in two or three meandering streams (Hong and Cho, 1983; Ichiye; 1983). The TWCW develops and spreads to the north from spring to summer and diminishes in strength from autumn to winter (Ohwada and Ogawa, 1966). Spatial and temporal variations of the characteristics of oceanic current condition in this study area are complicated horizontally or vertically. This complexity is caused by bottom topography and climatic conditions such as continental climate and the variability of monsoon (Nishimura, 1969; 1983).

MATERIALS AND METHODS

A total of 58 stations in the East Sea had been investigated once a year from 1988 to 1990 (Fig. 1). The first year survey had been done from 17 to 20 May, the second from 8 to 14 July and the third from 26 to 29 April. Chlorophyll-a concentrations as a biomass index of primary producer were measured *in vivo* with a fluorometer (Turner Design III) and calibrated by spectrophotometric method. For the measurements of chlorophyll-a concentrations of nano- and picoplankton (<20 μm) and picoplankton (<2 μm), the water samples were passed through 20 μm nylon mesh and membrane filter with 2.0 μm pore size, respectively. Primary productivity was determined using the C-14 uptake method (Parsons et al., 1984a). The same size classes used in the chlorophyll were adopted for the measurement of productivity of the samples. After incubation, the samples were filtered through 0.2 μm pore sized membrane filter and DPM (disintegrations per minute) of C-14 which had been assimilated into phytoplankton cells were measured. Besides biological data, some physicochemical data from Kim's (1990) and Ju's (1990) investigation results were cited for interpretation, which were collected simultaneously with the biological data.

RESULTS AND DISCUSSION

Physico-chemical Environments

The structure of physical environment is commonly expressed in terms of water properties such as water temperature, salinity and density. In spring, the average surface water temperature, salinity and sigma-t were 15.84℃, 34.47‰ and 25.38, respectively.

Lee (1991) made an account on relatively high surface temperature in this area by influx of TWCW and on significance of dissolved oxygen concentration with an interest in origin and movement of cold water mass. Vertically, dissolved oxygen maximum layer located shallower than 100 m where the temperature was 12-13℃, which was upper layer of thermocline. The difference between the saturation concentration and the observed concentration of oxygen for particular sample is a measure of the oxygen consumption which has

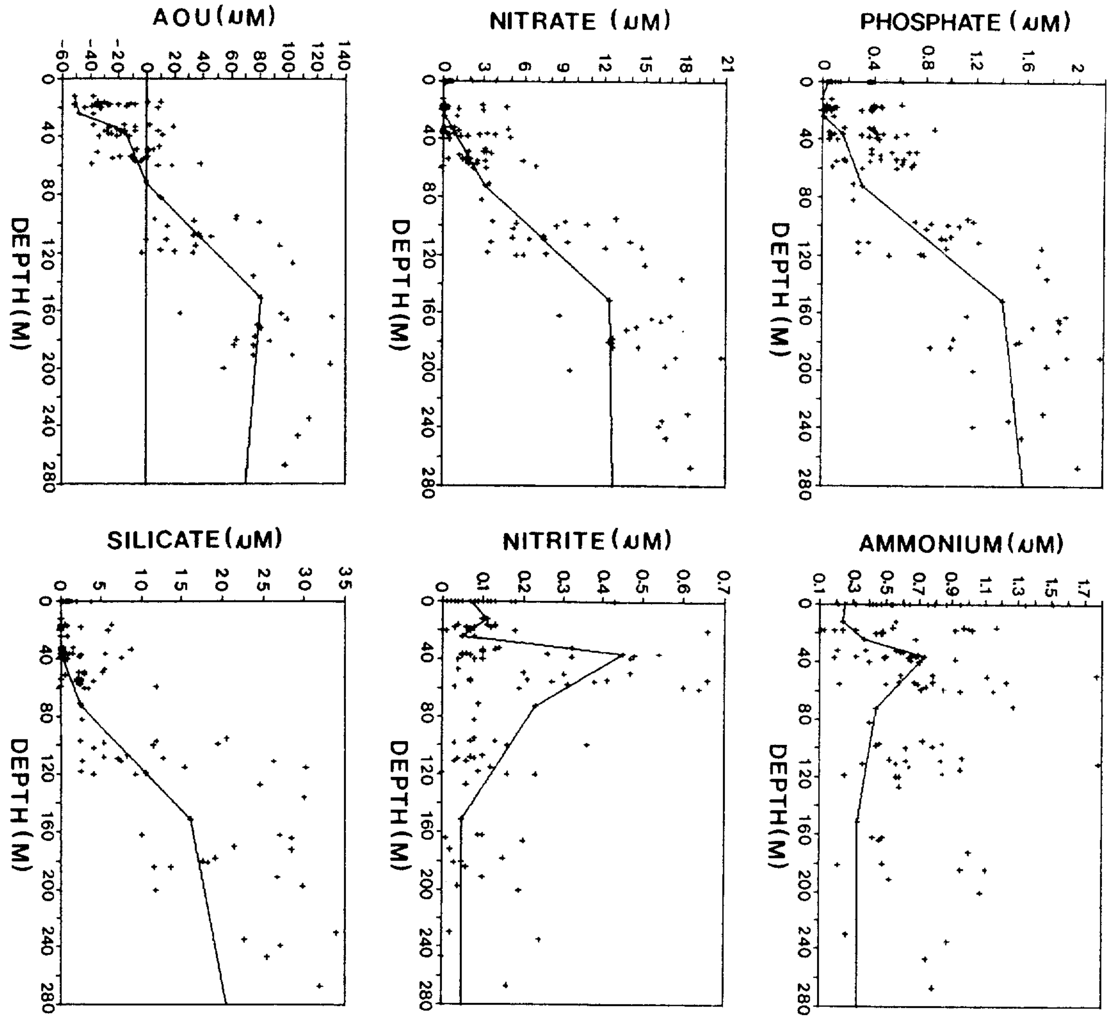

Fig. 2. Vertical distributions of AOU and nutrients concentrations in May, 1988 (AOU, Nitrate, Phosphate and Silicate data from Lee (1991); Nitrite and Ammonia data from Ju (1990)).

taken place in the water since surface saturation and is generally described as apparent oxygen utilization or AOU (Redfield et al., 1963). Dissolved oxygen concentration at surface is changed in connection with atmospheric pressure, salinity and water temperature and AOU appears 0 μM theoretically. But, in this study AOU was negative in upper layers (Fig. 2), due to supersaturation caused by active photosynthesis (Parsons et al., 1984b).

Low nutrient concentrations showed in upper layer but nitrate and phosphate concentrations increased with depth down to 160 m and became homogeneous below the depth. The vertical profiles of nitrite and ammonium showed similar trend with subsurface (40-60 m) maximum (Fig. 2). N/P ratio of the study area was 11.26 which is rather lower than the Redfield ratio (Redfield et al., 1963), and in surface water down to 60m, the ratio was 2.77 which is much lower value. Based upon the nitrate distribution, it could be convinced that the assimilation of nitrate was the most important limiting factor in primary production in the study area. In addition to nitrate depletion, silicate also depleted in the upper zone especially just above the chlorophyll maximum. Raymont (1980) discussed that Si/P ratio in western Atlantic ocean waters was about to 15. The result insinuated that silicate also might play the role of a limiting factor in the growth of phytoplankton, especially diatom, at the upper layer in this study area where Si/P ratio was 5.14.

Characteristics of Primary Production System

Distribution of standing stocks and chlorophyll-a

In the first cruise, the standing stoks of netplankton (>20 μm) were more than 10,000 Cells·ml^{-1} from surface to 40m depth at most stations. Nanoplankton (<20 μm) had much more standing stocks (>100,000 Cells·ml^{-1}) and occupied more than 90% out of total. Though nutrients concentrations were very low around the surface, it seemed to be mixed vertically with nutrient rich deep water (100-200 m) owing to the relative weak stratification in the upper layer. Park (1986) reported the fast regeneration of inorganic nutrient in this area. Therefore increase of the standing stocks were stimulated by the promotion of primary productivity at surface and subsurface waters. By the reason, AOU appeared with negative values in some upper layer waters and this phenomenon insinuated the area productive on the contrary (Parsons et al., 1984b).

The fractional biomass of nanoplankton was large portion to the total biomass of primary producer, which might be a characteristic of oceanic warm water (Berman et al., 1984). Quantitatively, the spherical forms constituted the dominant component of the phytoplankton in whole water mass accounting for 79% of total cell counts in the present study. The spherical forms were of a coccoid type, appearing either unicell or aggregates of a few cells, and varied in size between 1 and 3 μm. No attempt could be made to establish the taxonomic position of those tiny cells, although in the sense of the absence of well defined nucleus and color of plasma it might be assumed that they were cyanobacteria. These micro-organisms which make up the picoplankton group are widely distributed in the world oceans and can be responsible for the significant proportion of the primary production (Joint and Pomroy, 1986).

The presence of chlorophyll maximum layer had been reported in this study area (Shim and Park, 1986) and southwestern sea of Korea (Shim and Park, 1984). Chlorophyll maximum depth corresponded roughly to the base of euphotic zone either above or below the 1% of surface irradiance (30-40 m depth). When vertical mixing is intense and persistant, environmental conditions change more rapidly than abilities of phytoplankton adjustment. The cells acclimate to the average light condition in the mixed layer. On the contrary, the conditions of moderate or weak vertical mixing layer changes slower than the physiological adaptation by the phytoplankton so that the cells can adjust continuously to the new condition (Falkowski, 1980). According to Cullen's (1982) view, a subsurface chlorophyll maximum layer dose not always correspond to the phytoplankton standing stocks maximum layer and chlorophyll concentra-

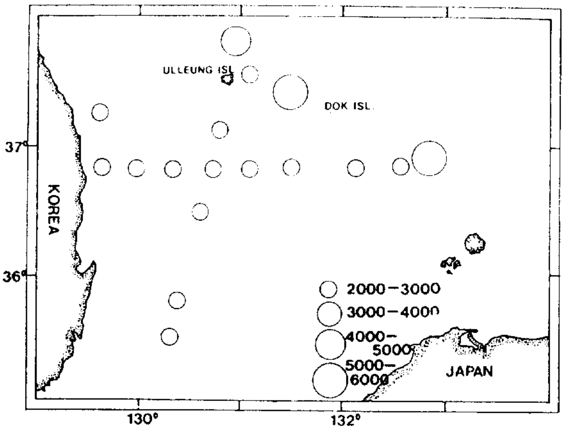

Fig. 3. Phytoplankton standing stocks at surface waters in July, 1989 (unit: Cells·ml^{-1}).

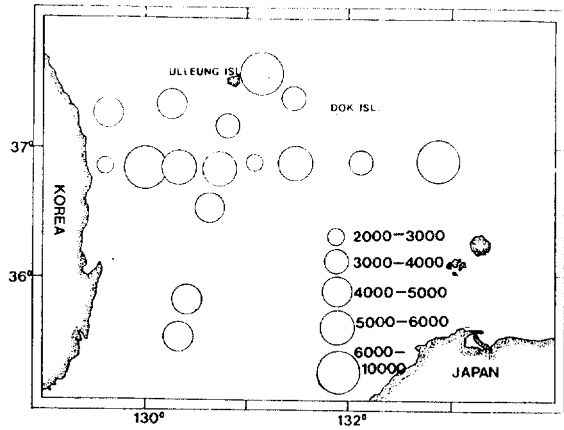

Fig. 4. Phytoplankton standing stocks at 40 m depth waters in July, 1989 (unit: Cells·ml^{-1}).

tions per unit cell number increase when the cells become shade adapted. At our sampling stations the increase of chlorophyll was accompanied by an increase of cell numbers. In addition, shade adaptation of phytoplankton might be done with an increase in chlorophyll contents per cell, so that it could be confident that the observed chlorophyll maximum at around 35 m does not only reflect shade adaptation to low light intensity but also represent a real increase in phytoplankton biomass. Chlorophyll maximum depth usually coincided with the upper zone of nutricline (40-60 m depth) rather than isopycnal surfaces (10-20 m depth), supporting the view that chlorophyll distributions were primarily influenced by nutrient supply.

Phytoplankton standing stocks of surface water in summer 1989 ranged 2,174-5,512 Cells·ml^{-1} and the proportions of nanoplankton were over than 80% among all stations. These standing stocks were much less than in spring 1988. Horizontal distributions of phytoplankton standing stocks were not varied largely (2,000-3,000 Cells·ml^{-1}) and relatively high concentrations showed in the vicinity of Ulleung Island and the end of eastward area of this study (Fig. 3). This result might be caused by relatively high primary productivity at the regions. Though surface water of the end of eastward area showed low nutrients level especially nitrogenous nutrients (<0.1 μM), subsurface water (40-60 m depth) showed relatively high nutrients concentration (65 m nitrate; 3.64 μM). This fact insinuated that high primary production might be possible at the subsurface waters and promoted rise of primary productivity (3,336 mgC·m^{-2}·day^{-1}) through the whole water column. The standing stocks at 40 m depth (2,443-8,425 Cells·ml^{-1}) were larger than at surface and showed more than 3,000 Cells·ml^{-1} at most stations (Fig. 4). The proportions of nanoplankton to the total standing stocks were significant at the depth as surface. And chlorophyll concentrations ranged from 0.5 to 14.85 μg·l^{-1} and those were variable a lot according to the water depths and stations. The percentages of nano- and picoplankton (<20 μm) were from 22.23 to 99.14% and over 80% at most stations. Consequently the significance of nano- and picoplankton was proved not only in spring but also in summer. While chlorophyll maximum layer was 40 m depth at most stations, that was occasionally formed at 20 or 65 m water depth. Therefore chlorophyll maximum layers in the area seemed to be formed between 20 and 60 m on the whole.

Surface water chlorophyll concentrations ranged from 1.47 to 7.40 μg·l^{-1} in spring 1990 and showed relatively high level (>4 μg·l^{-1}) along the east coast of Korea (Fig. 5). That seemed like typical neritic environmental characteristic of the water masses corresponded to relatively high water temperature area by the direct effect of TWCW. And

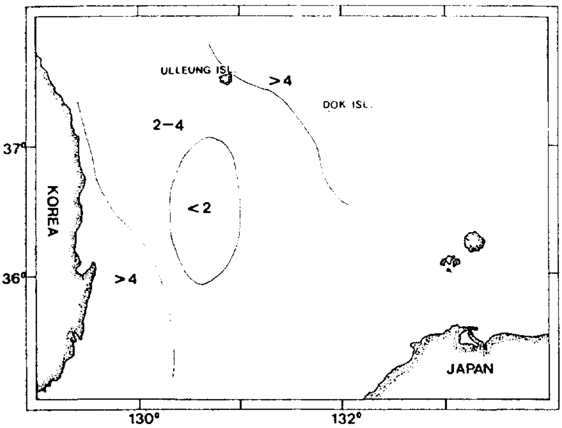

Fig. 5. Chlorophyll-a concentrations at surface waters in April, 1990 (unit: μg·l^{-1}).

relatively high chlorophyll concentrations (>4 μg·l^{-1}) were found in the eastnorthward area from the line between Ulleung Island and Dok Island. This phenomenon could be caused by the island effects and movement of water mass which had high nutrient concentrations. On the contrary, the central part of the study area showed relatively low chlorophyll concentrations (<2 μg·l^{-1}) (Fig. 5), there being oligotrophic stratified water mass. Nano- and picoplankton chlorophyll concentrations at surface water ranged from 1.26 to 4.26 μg·l^{-1} and this distribution pattern was similar to that of the total chlorophyll concentarations. However, nano- and picoplankton chlorophyll percentages to the total were less than 60% in the area where showed high chlorophyll concentration (>4 μg·l^{-1}) and more than 60% in the low chlorophyll (<4 μg·l^{-1}) area on the contrary. This result meant negative correlation between the total chlorophyll concentrations and nano- and picoplankton fractions. This corresponded to Shim and Bak's (1983) report that there was less proportion of nanoplankton biomass in neritic region than the proportion in oceanic region.

Very small sized (<2 μm) picoplankton chlorophyll proportions to the total chlorophyll were always larger than 29.25% and especially larger than 40% at the bottom depth of euphotic zone. It is ascertained that the biomass of picoplankton groups could be significant in this study area and the study on picoplankton groups is necessary.

Common result throughout the whole study period was a relatively large biomass of small cell sized phytoplankton groups, nano- and picoplankton. Dominance of small cell sized plankton (nano- and picoplankton) is common phenomenon in the oceanic waters and the same situation in this study area might have close correlation with the influx of TWCW.

Primary Productivity

Ocenic physico-chemical conditions including light irradiance, water temperature and fluctuations of the inorganic nutrients related to biological factors affect the phytoplankton primary productivity directly. Recent studies showed that the major nitrogen source for the phytoplankton growth might come from the pelagic regeneration by micro-sized heterotrophic plankton and macro zooplankton (Gilbert, 1982; Shim and Park, 1986; Park, 1986).

The depth integrated daily primary productivity ranged from 284 to 4,574 mgC·m^{-2}·day^{-1} (Table 1) and averaged to be 2,000 mgC·m^{-2}·day^{-1} in spring 1988 and 1990. Although primary productivity within the euphotic zone was high, ambient inorganic nitrogenous nutrient concentrations were too low to support the primary productivity by phytoplankton. When assuming C/N ratio to be 6.63, daily nitrogen requirement for phytoplankton averaged to be 25.58 mg at-N·m^{-2}·day^{-1} ranging from 3.57 to 57.53 mg at-N·m^{-2}·day^{-1} (Table 2). In a few stations, ambient nitrogenous nutrient concentrations integrated into the bottom of euphotic zone were lower than the daily nitrogen requirement by phytoplankton. Thus, if it had not been for the continuous nitrogen supplies, nutrient would have been depleted completly within a day by the phytoplankton assimilation. The present investigation has not assessed properly the supplies of nitrogenous nutrient but Shim and Park (1986) discussed the supplies of nitrogenous nutrient in details in this study area.

At the 2nd year (1989) summer investigation, primary productivity ranged from 444 to 3,605 mgC·m^{-2}·day^{-1} (Table 1) and averaged to be

Table 1. Primary productivities (PP) in the southern waters of the East Sea, Korea

Year	Station	Total PP	Nano & Pico PP (unit; $mgC \cdot m^{-2} \cdot day^{-1}$)	Pico PP	Nano & Pico Fraction (%)	Pico Fraction (%)
1988	A	382	158		41.36	
(May)	B	1,646	414		25.15	
	D	4,574	1,210		26.45	
	I	4,361	1,981		45.43	
	P	959	110		11.47	
	Q	284	56		19.71	
1989	C	1,167	954		81.73	
(July)	E	3,336	2,842		85.19	
	H	3,605	2,886		80.06	
	J	444	336		75.80	
	M	1,898	1,361		71.73	
	O	950	368		38.69	
1990	A	3,808	1,290		33.88	
(April)	C	3,909	2,711		69.35	
	E	1,616	1,053		65.16	
	F	1,678	861		51.31	
	G	2,109	1,001	171	47.46	8.11
	K	310	226	50	72.90	16.13
	L	2,769	1,553		56.09	
	M	2,877	1,861	229	64.69	7.96
	N	3,223	2,360	142	73.22	4.41

Table 2. The depth integrated daily nitrogen requirement by phytoplankton (NRP) and ambient inorganic nitrogenous nitrogen concentration in May 1988.

Station	NRP ($mg\ at\text{-}N \cdot m^{-2} \cdot day^{-1}$)	Nitrogen conc. ($mg\ at\text{-}N \cdot m^{-2}$)
A	4.81	139.3
B	20.70	19.1
D	57.53	53.2
I	54.86	43.7
P	12.06	129.2
Q	3.57	28.9

about 1,900 $mgC \cdot m^{-2} \cdot day^{-1}$. Though this value was slightly lower than the value in spring, active primary production must be accomplished from the euphotic zone in summer, too. At the sight of regional differences of primary productivities, relatively high productivity (>3,000 $mgC \cdot m^{-2} \cdot day^{-1}$) was measured in the central and eastern parts of this study area. From the three years (1988-1990) results, it could be said that relatively high production appeared at the adjacent waters of Dok Island and southwestern or southeastern ward waters of the island.

The fractions of nano- and picoplankton to the total primary production were from 38.69 to 85.19% in summer 1989 and those were over 70% at most stations (Table 1). Therefore the significance of nano- and picoplankton was convinced at the point of not only standing stocks or chlorophyll concentration but also primary production. And the fractions were from 33.88 to 73.22% in spring 1990 and the average was 59.34%. Especially picoplankton (<2 m) productivities were measured at the 3rd survey (spring, 1990) and ranged from 50 to 229 $mgC \cdot m^{-2} \cdot day^{-1}$. These picoplankton productions formed from 4.41 to 16.13% of the total primary production in this study area (Table 1), which were lower than Shim et al.'s (1991b) result (19.64-81.45%) in neritic waters. However, it was not easy to compare present result directly with the previous one because of the difference of environmental conditions and experimental methods; while Shim et al. (1991b) measured the picoplankton productivities at thermal effluent region in winter season and in the water passed through 3 μm pored membrane filter, 2 μm pored membrane filter was used in this study. As we have explained above, picoplankton chlorophyll concentrations were over 29.25% of the total chlorophyll concentrations in this study area and especially, those formed about 40% at around the subsurface layer. From the result we could say that the picoplankton proportions of the total phytoplankton biomass were larger than those of the total primary production (4.41-16.13%) and the photosynthetic activity of picoplankton group seemed not to be as high as that of larger cell sized groups. Consequently, we can say that it is indispensable to measure the picoplankton biomass and productivity for the study on primary production system in this study area.

SUMMARY

Primary producer biomass and productivity in the southern waters of the East Sea (Sea of Japan) were investigated three times in conjunction with physico-chemical factors from May 1988 to April 1990. The water column was weekly stratified. Ambient nutrient concentrations were markedly depleted in the upper layers and nitrogen was major limiting nutrient. Silicate also seemed to play the role of a limiting factor in surface waters. Subsurface chlorophyll maxima were continuously observed at the lower part of the euphotic zone but the depths were more or less varied temporally. The depth corresponded to the nutricline rather than isopycnal surfaces, supporting the view that phytoplankton biomass distributions and primary productions were primarily influenced by nutrient supply.

The primary productivity of phytoplankton averaged to be 2,000 $mgC \cdot m^{-2} \cdot day^{-1}$ and the standing stocks within the euphotic zone were relatively high, but ambient inorganic nitrogenous nutrient concentrations were too low to support the high production. This implied that there was active recycling of nutrients. In spite of low nutrient concentrations, primary producer biomass and production were relatively high in this study area. And the contribution of nano- and picoplankton on the primary production system, especially spherical form (1-3 μm) which seemed to be cyanobacteria, was important.

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