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Studies for the Sustainable Management of Oyster Farms in Pukman Bay, Korea: Estimate of Primary Production

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To develop sustainable management strategies for oyster farms in Pukman Bay, Korea, we estimated primary production using a numerical model. Because oysters are filter feeders, estimations of primary production (*PP*) are essential in developing management strategies. The daily *PP* ranged from 0.07 to 1.5 $gC/m^2/d$ and showed significant spatial variations. The spatial distribution of *PP* was strongly associated with hydrodynamic features, and distinct patterns were observed in three different regions. In the inner bay, high *PP* was directly influenced by urban and agricultural sewage. The middle part of the bay had low *PP*, whereas *PP* in the outer area was high. *PP* was relatively low during the main oyster growth season, from late autumn to early winter. These findings represent important information for developing a management model for oyster farms in Pukman Bay.

Key words: Pacific oyster, Primary production, Sustainable management Introduction

Introduction

Pukman Bay is a semi-enclosed bay on the western side of Tongyeong Peninsula, Korea. Many oyster farms are located in this area, with a total annual production of approximately 1,193 tons of oysters (fresh weight) per year. The foreshore has recently been reclaimed to provide new land area, resulting in an increase in domestic sewage flowing into the bay. Water quality in Pukman Bay is also adversely affected by a drainage pump station and a domestic sanitary station situated nearby. The increased inflow of anthropogenic pollutants causes frequent eutrophication (Choi et al., 1991; Choi and Jeong, 1998), phytoplankton blooms (Kim, 2006), and oxygen deficiencies within the bay waters (Choi et al., 1991). Oyster farms have been removed from the inner part of the bay, leading to a marked reduction in annual production. An urgent need has emerged to develop appropriate management strategies for oyster farms in the bay. To develop such strategies, the provincial government has launched a project to estimate Pukman Bay's potential for oyster culture.

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Several factors must be considered in the management of oyster farms. Studies have reported various aspects of oyster culture conditions in Tongyeong waters, including culture density (Cho and Kim, 1977), water and sediment quality (Cho and Kim, 1978; Cho, 1980; Yoo et al., 1980; Lee, 1993; Choi et al., 1997), and primary production (Choi et al., 1991; Cho et al., 1982). However, few studies have examined self-purification (Choi et al., 1991) and water quality, (Choi, 1995; Choi and Jeong, 1998), and no studies have examined primary production in Pukman Bay.

Phytoplankton is a primary producer that accounts for 95% of organic matter production, making it a key factor in both the distribution and the production rate of filter-feeding bivalves. Spatial and temporal distributions of phytoplankton are affected by various factors, including nutrients, water temperature, irradiance, and the attenuation coefficient of irradiance. The high variances associated with these factors make it difficult to measure primary production in coastal waters. However, an accurate estimation of primary production is essential for evaluating the potential yields of oyster farms because oysters are filter feeders that rely solely on their ambient environment as an energy source (Lee et al., 1991).

To determine optimal oyster culture density, the primary production rate must be estimated. That is, we should gather preliminary data on food availability prior to estimating carrying capacity. In this context, the aim of this study is to estimate primary production in Pukman Bay, Korea. This information will enable the development of appropriate strategies for managing oyster farms in the area.

Materials and Methods

Seawater analysis

Seawater was sampled monthly at various depths at eight sites from October 1994 to April 1996 (Fig. 1) using a Niskin sampler. Water temperature, salinity, and dissolved oxygen were measured by CTD (SBE-19, Seabird Electronic Inc., USA). Chlorophyll-*a* levels were determined as described by Parson (1984).

Estimation of primary production

To estimate primary production, a numerical model was developed to predict photosynthetic rate from water temperature, solar irradiation, and chlorophyll-*a* content (Jeong et al., 2001). The model is described below.

Solar irradiance and attenuation coefficeient (k)

Solar irradiance at the sea surface was determined using a LI-1000 datalogger equipped with an LI-190SA quantum sensor (LI-COR, Nebraska, USA; mol/m^2/sec), which was situated on the roof of our laboratory. Depth-dependent variations in irradiance were determined using an LI-193SA spherical underwater quantum sensor (LI-COR, USA). The data were normalized with the exponential attenuation phase. The irradiance at a given depth in the water column (C_z) is estimated by equation (1) as follows:

$$C_Z = C_0 \times e^{-k \cdot Z} \qquad (1)$$

where C_0, k, and z are irradiance at the surface, attenuation coefficient, and depth (m), respectively. The euphotic depth was assumed to be the depth at which irradiance was 0.1×10^{15} quanta/cm^2/sec.

Relationship between irradiation and photo-synthesis

Primary production was estimated following Steemann-Nielsen (1975) using a hyperbolic function between irradiation and photosynthetic rate, which was saturated from 20.6×10^{15} to 90×10^{15} quanta/cm^2/sec at 20°C (Fig. 2).

Relationship between water temperature and photosynthesis

The saturation point of the hyperbolic relationship

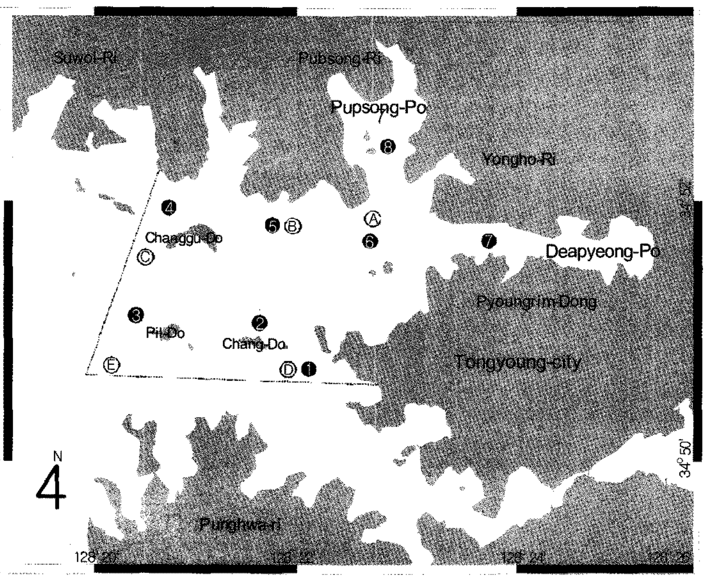

Fig. 1. Sampling sites for seawater and hydrodynamic measurements. Closed circles indicate sites where water and primary production were measured. Open circles indicate sites of hydrodynamic measurements.

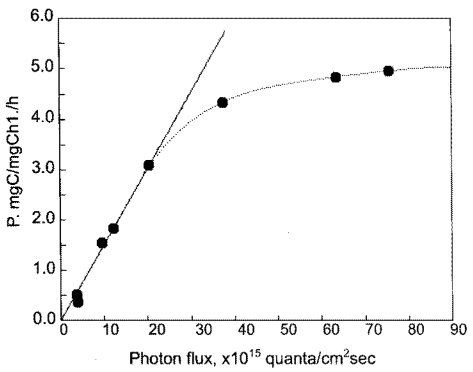

Fig. 2. Relationship between photon flux and photosynthetic rate (P) at 20°C (Steemann-Nielsen, 1975). The photosynthetic rate showed a hyperbolic relationship with photon flux saturation point, 20.6×10^{15} quanta/cm^2/sec.

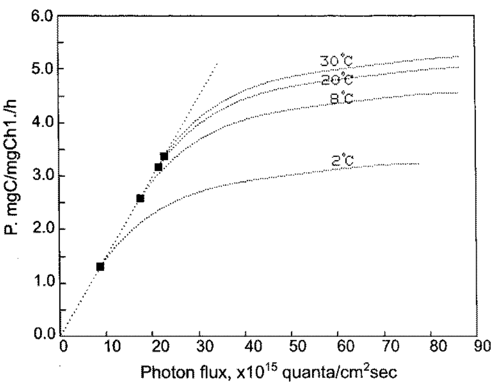

Fig. 3. Photosynthetic rate vs. water temperature (Steemann-Nielsen, 1975). The saturation point decreases with decreasing water temperature.

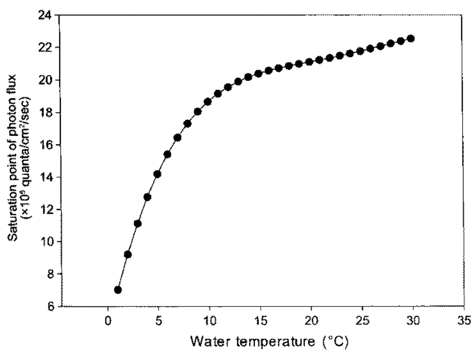

Fig. 4. Variation of saturation point in relationship between irradiance and photosynthetic rate, showing biquadratic regression with water temperature (modified from Steemann-Nielsen, 1975).

increases with increasing water temperature (Steemann-Nielsen, 1975; Fig. 3). Here, the relationship was modified to a biquadratic model between water temperature and saturated irradiation, as shown in Fig. 4.

Daily primary production

To estimate primary production, irradiance data must be normalized to 20°C. If irradiance at depth z (Q_z) is less than the saturation point ($Q_{R(t)}$), a direct estimation can be made using the photon flux-photosynthetic rate relationship. If Q_z exceeds $Q_{R(t)}$, the following two-step normalization is carried out:

$$\Delta Q = Q_{S,20} - Q_{r,t}$$
$$\Delta P = P_{(20)} - (a_P \cdot Q_{R(t)}) \ (mgC/mgChl/h) \tag{2}$$

where ΔQ is the difference in saturation points between 20°C and t°C, ΔP is the difference between photosynthetic rates at 20°C and at t°C, and a_P is the linear slope of the photon flux-photosynthetic rate below the saturation point. Therefore, the photosynthetic rate above 20°C can be obtained using the following equation:

$$PPC_{z,t} = P_{(20)} - \Delta P (mgC/mgChl/h), \quad t > 20°C \tag{3}$$

To determine the relative photosynthetic rate with respect to chlorophyll-*a*, $PPC_{z,t}$ is multiplied by chlorophyll-*a* to calculate the unit time/water volume-dependent primary production (P_z), as follows:

$$P_z \ [mgC/m^3/h] = PPC_{(z,t)} \ [mgC/mgChl/h] \times chl-a \ [mg/m^3] \tag{4}$$

The incident primary production of a water column (P_H) can be obtained from the integral of P_z at each depth and euphotic zone, as follows:

$$P_H \ [mgC/m^2/h] = \sum_{Z=0.5}^{Z_d} P_z \ [mgC/m^3/h] \tag{5}$$

where Z and Z_d are the depths of the water column and euphotic zone, respectively. From equation (5), daily primary production can be cal-culated from the integral of P_H during the irradiance period:

$$PP_{day}(mgC/m^2/day) = \sum_{H=1}^{H_{rad}} PP_{(H)}(mgC/m^2/h) \tag{6}$$

Evaluation of primary production

To define zones of primary production within the bay, a three-dimensional hydrodynamic model (Nakata et al., 1983) was used to show tidal currents. We measured the current fields at six stations (A to F in Fig. 1) on 21 and 22 October 1994. The input parameters for the model are listed in Table 1. We then evaluated the geographical distribution of primary productivity within Pukman Bay using the hydrodynamic and primary production data.

Table 1. Parameters for calculating a hydrodynamic model for Pukman Bay

Parameters	Values
Mesh size	$\Delta x = \Delta y$ = 125 m
Water depth	Chart datum + MSL
Time interval	5 sec
Level	1: 0-4 m 2: 4-8 m 3: >8 m
Tidal level at open boundary	82-85 cm
Water temperature and salinity at open boundary	1: 25°C, 18 psu 2: 25°C, 18 psu 3: 25°C, 18 psu
Coriolis coefficient	$f = 2\omega \sin\theta$
Surface friction coefficient	0.0013
Internal friction coefficient	0.0013
Bottom friction coefficient	0.0025
Horizontal diffusion coefficient	3.5×10^4(cm^2/sec)
Horizontal viscosity coefficient	3.5×10^4(cm^2/sec)
Wind speed	0.0 m/sec
Calculation time	5 cycles

Statistical analysis

Estimated *PP* data were analyzed using ANOVAs to characterize spatial distribution. *Post-hoc* analyses were carried out using the Scheffe's test with a 95% significance level.

Results and Discussion

Water temperature ranged from 6.2 to 26.2°C (Table 2). We did not observe any trends in water temperature with respect to geographical location; however, significantly lower water temperatures were recorded during winter from the inner part of the bay, which may have been a result of the shallow water depth.

Chlorophyll-a content ranged from 0.91 to 10.45 mg Chl-a/m^3 (Table 3). The largest phytoplankton bloom was observed in June 1995 (mean 4.63±2.7 mg Chl-a/m^3), apparently related to seasonal changes. Mean chlorophyll-*a* content was higher in the western part of the bay, which receives greater discharge of domestic and agricultural wastes (Jeong and Cho, 2006).

Salinity ranged from 31.32 to 34.99 psu at the surface and from 31.52 to 34.99 psu at lower depths. A clear seasonal effect was observed, with higher salinity in winter and lower salinity in fall (data not shown).

Table 2. Water temperature (°C) at each sample site in Pukman Bay

Month	Sample site							
	1	2	3	4	5	6	7	8
Oct. 1994	20.7	21.2	21.3	21.4	21.3	21.0	20.9	21.1
Nov.	17.2	17.8	17.9	17.8	17.7	16.7	16.7	16.7
Dec.	11.5	11.9	11.6	12.8	11.8	10.6	10.3	10.1
Jan. 1995	7.1	7.7	9.0	9.2	8.7	6.3	6.0	6.2
Feb.	8.8	9.2	9.4	9.5	9.1	7.6	7.5	7.4
Mar.	10.5	10.3	10.4	10.6	10.3	10.0	9.9	10.0
Apr.	13.6	13.5	13.2	13.2	13.7	14.1	14.1	13.9
May	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
Jun.	19.4	20.2	20.0	20.3	20.3	20.5	20.6	20.3
Jul.	21.0	24.0	23.0	23.0	23.0	23.0	23.0	23.0
Aug.	23.5	26.2	24.3	25.2	25.2	26.0	26.0	26.0
Sep.	21.2	21.2	21.2	21.1	21.2	21.6	21.9	21.8
Oct.	20.7	21.0	21.0	21.0	21.0	21.0	21.1	21.2
Nov.	14.6	14.6	14.7	14.5	14.7	14.7	14.6	14.9
Dec.	11.0	11.2	11.3	10.8	10.0	10.6	10.5	10.5
Jan. 1996	8.1	8.0	7.3	8.5	8.3	6.6	6.8	6.7
Feb.	8.6	8.5	9.5	8.5	7.4	7.4	7.0	7.6
Mar.	10.8	10.6	10.5	10.4	10.3	10.5	10.5	10.6
Apr.	15.0	15.3	15.5	15.6	15.8	16.0	16.0	16.2

Table 3. Chlorophyll-a (mg Chl/m^3) at eight sites in Pukman Bay

Month	Sample site							
	1	2	3	4	5	6	7	8
Oct. 1994	3.69	1.49	0.98	1.42	1.43	4.05	2.66	6.43
Nov.	4.87	2.58	1.02	1.46	1.44	4.29	3.50	6.03
Dec.	4.94	2.77	1.43	1.55	1.35	4.77	5.18	7.68
Jan. 1995	4.17	2.66	1.46	1.30	1.28	4.77	4.87	7.13
Feb.	2.46	1.43	1.36	1.15	1.14	3.62	3.53	7.09
Mar.	1.10	0.91	0.92	0.91	0.99	1.71	1.62	1.88
Apr.	3.98	1.38	2.89	1.16	2.72	2.55	2.42	3.89
May	5.61	2.19	3.14	1.41	2.98	3.73	3.66	7.01
Jun.	5.71	2.67	3.75	1.61	4.66	3.80	4.39	10.45
Jul.	3.13	2.32	2.67	1.57	2.86	2.82	4.66	8.93
Aug.	1.84	1.85	2.75	1.73	3.14	2.21	4.03	6.92
Sep.	3.64	1.76	2.66	2.21	2.77	3.25	4.65	5.96
Oct.	3.82	1.96	2.13	2.29	3.03	3.59	3.74	4.86
Nov.	3.51	1.66	1.83	1.98	2.97	3.24	3.48	4.41
Dec.	3.61	1.82	1.79	1.92	2.55	4.62	7.57	2.46
Jan. 1996	3.68	1.69	1.66	1.87	2.49	4.56	7.53	3.06
Feb.	4.19	1.97	1.77	1.90	2.57	4.50	7.44	3.27
Mar.	3.04	2.04	1.5	1.50	1.96	1.78	1.95	3.50

Dissolved oxygen (DO) ranged from 4.21 to 9.95 mg/L at the surface and from 1.01 to 9.90 mg/L at lower depths. In the summer, oxygen deficiencies were observed at sites 6, 7, and 8 (1.01-3.28 mg/L). Fig. 5 shows the mean and standard deviations of DO at each sample site, revealing wide fluctuations in the inner part of the bay. Site 5 was located on the boundary of this area.

The observed spatial variations in DO may result from hydrodynamic features and may identify the source of pollutants. Pukman Bay was hydrody-

Table 4. Primary productivity (mg C/m^2/d) per unit area at eight sites in Pukman Bay

Month	Sample site							
	1	2	3	4	5	6	7	8
Oct. 1994	546.9	236.6	95.6	71.6	91.1	87.5	331.4	233.3
Nov.	456.7	214.9	258.9	95.5	143.2	128.3	382.1	311.7
Dec.	655.6	218.3	237.1	114.6	130.2	110.7	406.6	431.8
Jan. 1995	785.8	377.0	295.3	163.7	151.1	163.4	567.1	585.8
Feb.	808.1	357.0	215.1	221.1	159.3	236.3	475.8	437.6
Mar.	140.0	128.2	100.8	76.4	88.3	82.1	155.9	134.1
Apr.	435.6	598.8	197.6	587.4	161.8	409.4	375.0	268.7
May	752.7	626.4	253.0	605.3	190.3	482.9	546.6	564.7
Jun.	1527.1	832.8	424.9	472.3	266.8	1205.2	314.1	304.2
Jul.	779.9	566.3	455.1	493.6	302.0	518.1	531.9	650.4
Aug.	810.0	478.1	374.0	587.8	328.8	696.3	411.4	570.4
Sep.	389.0	609.7	188.5	427.9	229.2	371.3	402.9	529.6
Oct.	344.1	469.9	422.8	186.8	463.6	372.8	774.5	664.9
Nov.	495.5	351.0	220.4	211.4	262.9	297.0	395.4	424.6
Dec.	291.5	609.7	129.4	149.8	204.0	157.8	605.7	930.7
Jan. 1996	205.3	446.1	188.1	193.3	212.7	151.4	318.3	481.4
Feb.	404.5	525.0	207.2	232.1	214.2	171.3	611.9	916.9
Mar.	440.0	380.2	260.6	195.6	166.3	282.3	222.3	270.5
Apr.	529.1	808.7	577.6	328.5	331.1	298.1	286.3	323.9

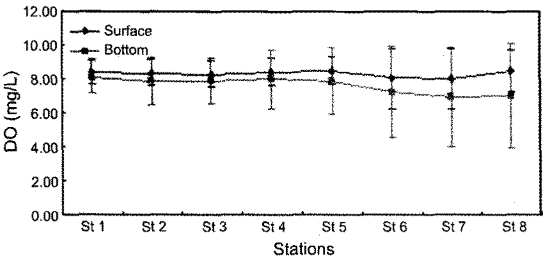

Fig. 5. Spatial distribution of mean dissolved oxygen (DO) ± standard deviation (vertical bars) at eight sites. Stations at inner regions of the bay (sites 6, 7, and 8) had low DO and high variance, reflecting unstable environmental conditions compared with those at outer areas of the bay (sites 1 and 2).

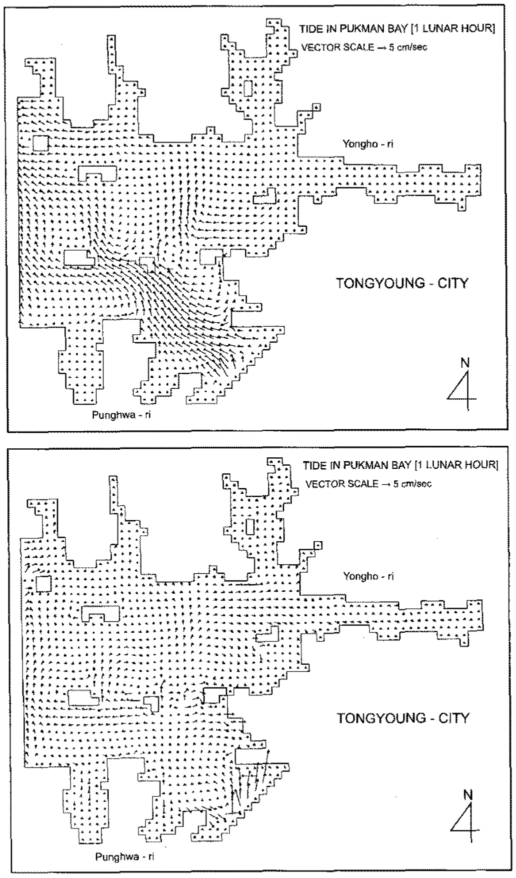

Fig. 6. Computed tidal residual current at level 1 (upper) and level 2 (lower) in Pukman Bay. A strong northward residual current existed at level 1, while the current moved towards the inner bay region at level 2.

namically divided by a residual tidal current, which flowed northward at level 1 and westward at level 2 between Chang Island and Hang Island (Fig. 6) (Jeong, 1999). This residual current barrier is expected to reduce the accumulation of pollutants by carrying them into open waters. Undiffused enrichment may be retained within level 1 by the residual tide and then returned to the inner area of the bay by the residual tidal flow at level 2.

The relationship between photosynthesis (*P*) and irradiance (*I*) is fundamental in primary productivity studies, with the *P-I* curve reflecting environmental conditions (Harrison and Platt, 1980; Falkowski, 1981). To determine the growth rate of phytoplankton, samples are usually incubated under natural or

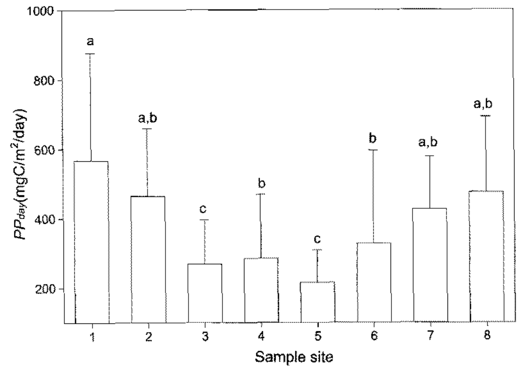

Fig. 7. Spatial distribution of mean PP_{day} at each site in Pukman Bay (ANOVA, P<0.001).

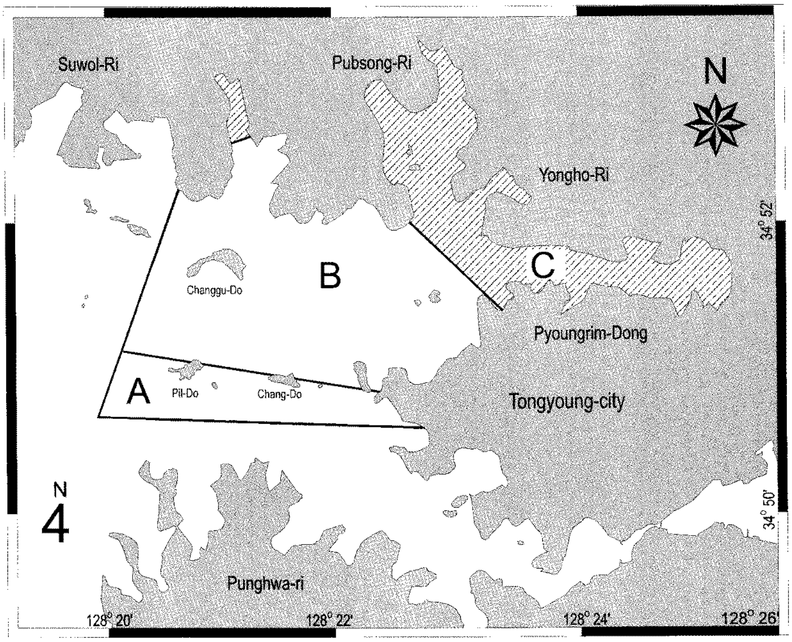

Fig. 8. Predicted regions of productivity in Pukman Bay. Three regions of productivity were designated: (A) high-yield area with high food availability; (B) low-yield area, and (C) area unavailable for oyster farming because of heavy pollution load from nearby inhabited areas.

artificial light for a fixed time period, commonly 2-4hours, and production is traced using radioactive agents; however, the *P-I* relationship during the incubation time varies significantly with the characteristics of the ecosystem (Macedo et al., 2002). In this study, we used a numerical approach to determine the *P-I* relationship, as described by Steemann-Nielson (1975). Several ecological models have used a numerical model to estimate primary production (Cho et al., 1996; Kitazawa et al., 2002; Nunes et al., 2003; Mizumukai et al., 2008). The growth rate determined in our study, 0.1507 h^{-1} (ca. 1.9 d^{-1}), lies within the typical values of 0.55-3.40 d^{-1} suggested by Collins and Wlosinski (1983).

*PP*day^{-1} ranged from 0.07 to 1.5 g C/m^2/day (Table 4), which is generally acceptable for coastal productivity in Korean coastal waters (Chung and Park, 1988; Park et al., 2001). The lowest production, observed at site 5, may have resulted from the hydrodynamic characteristics that limited the enrichment supply. Sites 7 and 8 were highly productive (Fig. 7) due to an algal bloom that occurred throughout the experimental period. Although production was high, species diversity was extremely low (Jeong and Cho, 2006).

Pukman Bay has three distinct regions of *PP* that are closely associated with tidal current features, especially within level 1 (Fig. 8). Relatively high productivity was measured in the inner part of the bay (C), including sites 6, 7, and 8 (site 8: 69.4-232.9 mgC/m^3/day). This finding is directly attributable to inflows of urban and agricultural sewage. Significant seasonal changes in *PP* observed at site 8 were related to precipitation; however, *PP* at sites 6 and 7 was relatively stable throughout the experimental period. *PP* was low in the middle area of the bay (B; including sites 3, 4, and 5), reflecting the interruption of terrigenous nutrients by the eddy tide around Changgu-Do. Within this area, little variation in *PP* was observed throughout the study period due to the tidal residual current. The outer part of the bay (A; including sites 1 and 2) showed the highest *PP*, which was probably a result of constant enrichment from the Tongyeong sewage disposal plant. In this area, large variations in PP were related to the tidal conditions (i.e., tidal ebb and spring tides).

Primary production was lower from late autumn to early winter than it was in spring and summer (Uye et al., 1987; Lee et al., 1991; Jo, 1988). To estimate carrying capacity, seasonal variations in food availability should be considered to determine the optimal density and/or scale of aquaculture operations in

Pukman Bay.

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