RESEARCH ARTICLE

Estimation of primary production of the waters around rack oyster farm at Wando, Korea

Woo-Geon Jeong[1] and Sang-Man Cho[2]*

Abstract

To establish a comprehensive management strategy, as part of the optimization of cultural practice for an oyster rack culture system, we used a numerical model to estimate the primary production in the waters on the eastern coast of Wando island, South Korea. The estimated primary production ranged from 17.12 to 1052.55 mgC m^{-2} day^{-1} (204.22 ± 224.75 mgC m^{-2} day^{-1} in average). Except for the times of peak phytoplankton blooms, the estimated primary production (PP) was consistently under 200 mgC m^{-2} day^{-1}, which is more similar to the value of PP measured off the western coast of South Korea than the southern coast. No clear relationship was observed between nitrogen content and rainfall with the exception of heavy rainfall events, indicating that precipitation might not be the main source of nutrients in these waters. No clear influence was observed from Doam tidal discharge, located 24 km north from these waters due to main tide comes in this area from the channel between Gunwe-myeon in Wando island and Pukpyeong-myeon in Haenam-gun. Because of the shallow water depth and strong tidal current, resuspension of sediments, which causes an input of nitrogen into the system, could be easily caused by even mild wind and the infrequent passing of ships. Microscopic examination of the phytoplankton composition showed additional contribution of benthic species such as *Paralia sulcata* into the waters, which increase the productivity of oyster farms in the waters. The availability of nitrate and phosphate for primary production was temporarily limited throughout most of the spring and autumn blooming season.

Keywords: Pacific oyster, Primary production, Oyster rack culture, Wando

Background

Oysters are suspension feeders that graze phytoplankton in the surrounding water column. This feeding behavior is facilitated by the cilia located on the gill filaments. These filaments generate water currents over the gills, select for food particles from the water column, transport food particles towards the mouth, and reject pseudofeces onto the mantle (Newell and Langdon 1996). Since the velocity field for feed behavior is highly restricted within organism's microenvironment (Uslu and Pekkan 2016), primary production could be a key factor in determining the productivity of oyster farms.

The present study site is located on the tidal flat of the eastern coast of Wando, which is positioned in narrow waterway between Wando and Gogeum Island. This area was previously well known for *Porphyra* aquaculture. Annual production in this region accounted for ~ 22% of national production in South Korea; however, an environmental change linked to changing demographic and industrial development means that *Porphyra* aquaculture has ceased in the tidal flats in Wando (Lee 2006; Han and Cho 2013). As an alternative fishery in the tidal flats, oyster rack culturing was introduced as a pilot project in 2013 (Cho et al. 2013a). Here, we optimized several conditions to achieve the maximum sustainable yield (MSY) in these oyster rack cultures (Han and Cho 2013).

To ensure the successful management of oyster culture, many factors must be considered, but primary production is one of the most vital to achieving the MSY. Since oysters are filter feeders that rely solely on the surrounding environment as an energy source, an accurate estimation of primary production (PP) is

* Correspondence: gigas@kunsan.ac.kr
[2]School of Applied Marine bioscience, Kunsan National University, Gunsan 573-701, Korea
Full list of author information is available at the end of the article

essential to evaluate the potential yields in oyster farm (Lee et al. 1991). In this study, we estimate the PP to optimize the cultural practices (e.g., cultural density, nursery technique) that can yield crucial information on the best practices for managing an oyster farm.

Methods

Seawater analysis

Seawater was sampled monthly at the surface of five sampling sites from June 2011 to December 2012 (Fig. 1) using a Niskin sampler. Water temperature, salinity, and dissolved oxygen (DO) were measured by multiprobe system (YSI 556, YSI, Ohio, USA). Chlorophyll-a content was determined as described by Parson et al. (1984) after filtration of seawater using GF/C filter. Dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) were determined followed by Korean standard method for marine environment (Fisheries 2013).

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. 2009). The model is briefly described below.

Solar irradiance and attenuation coefficient (k)

Solar irradiance at the sea surface was determined using an LI-1000 datalogger equipped with an LI-190SA quantum sensor (LI-COR, Nebraska, USA; mol m^{-2} s^{-1}), which was situated on the roof of our laboratory. Depth-dependent variations of irradiance in the water column were determined using an LI-193SA spherical under-water 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 Eq. (1) as follows:

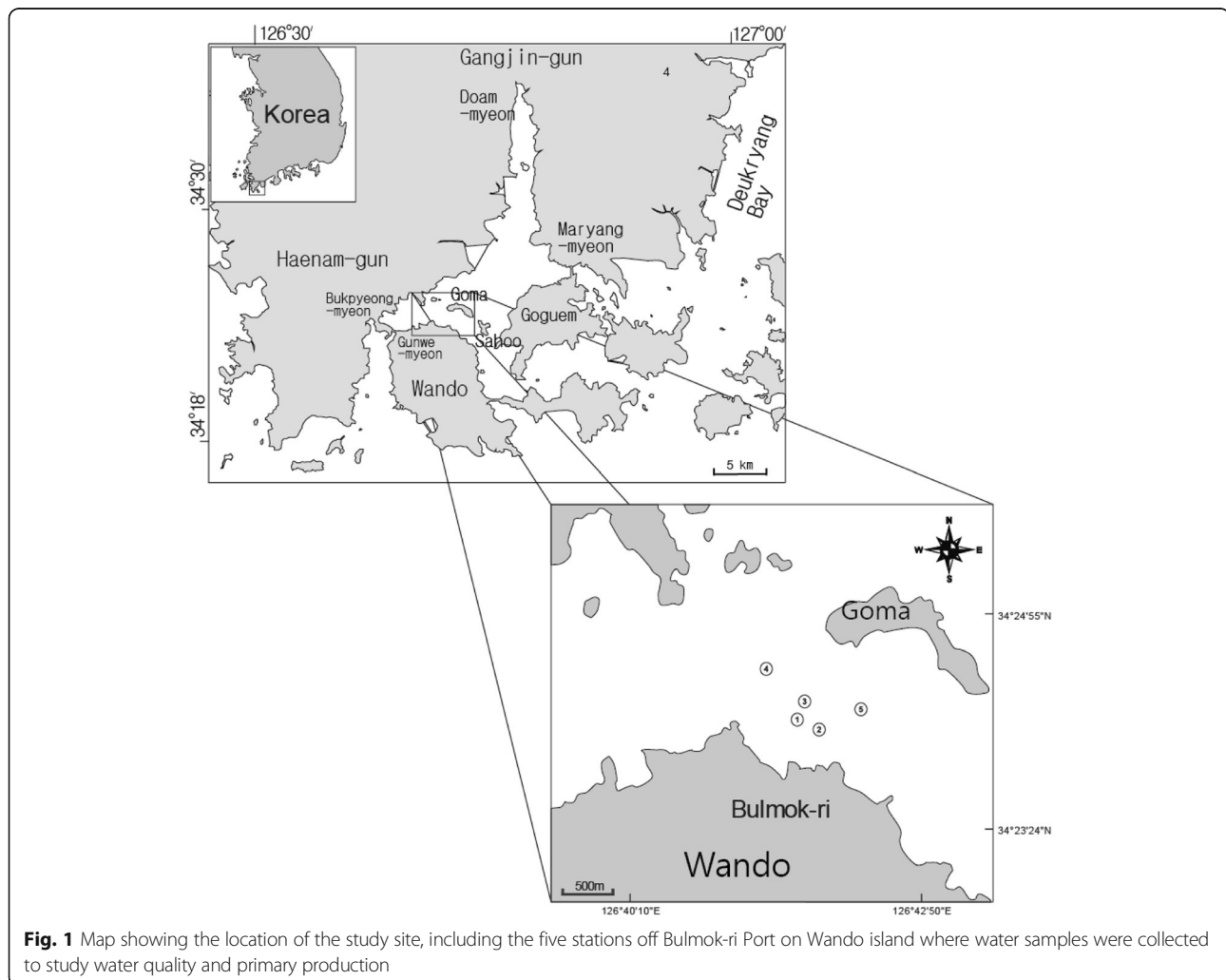$$C_Z = C_0 \times e^{-k \cdot Z}, \tag{1}$$

Fig. 1 Map showing the location of the study site, including the five stations off Bulmok-ri Port on Wando island where water samples were collected to study water quality and primary production

where C_0, k, and Z are irradiance at the surface, attenuation coefficient, and depth (m), respectively. In the study, the total water column was considered as a euphotic zone to be included in the estimation of primary production because of the shallow depth not over the 3 m even at full tide.

Relationship between irradiation, water temperature, and photosynthesis

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} s^{-1} at 20 °C. The saturation point of the hyperbolic relationship increases with increasing water temperature (Steemann Nielsen [1975](#)). Here, the relationship was modified to a biquadratic model between water temperature and saturated irradiation.

Daily primary production

To estimate the 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:

$$\begin{aligned} \Delta Q &= Q_{S,20} - Q_{r,t} \\ \Delta P &= P_{(20)} - \left(a_P \cdot Q_{R(t)} \right) \left(mgCmgChl^{-1}h^{-1} \right), \end{aligned} \quad (2)$$

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:

$$PPC_{z,t} = P_{(20)} - \Delta P \left(mgCmgChl^{-1}h^{-1} \right), \quad t > 20^{\circ}C \quad (3)$$

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:

$$P_z \left[mgC \ m^{-3}hr^{-1} \right] = PPC_{(z,t)} \left[mgCmgChl^{-1}h^{-1} \right] \quad (4)$$
$$\times chl-a \left[mgm^{-3} \right].$$

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:

$$P_H \left[mgCm^{-2}h^{-1} \right] = \sum_{Z=0.5}^{Z_d} P_z \left[mgCm^{-3}h^{-1} \right], \quad (5)$$

where Z and Z_d are the depths of the water column. From Eq. ([5](#)), the daily primary production can be calculated from the integral of P_H during the irradiance period:

$$PP_{day} \left(mgCm^{-2}day^{-1} \right) = \sum_{H=1}^{H_{rad}} PP_{(H)} \left(mgCm^{-2}h^{-1} \right). \quad (6)$$

Statistical analysis

All data were represented, and estimated PP data were analyzed using ANOVAs to characterize spatial distribution. Post hoc analyses were carried out using the Tukey test with a 95% significance level.

Results and discussion

Water temperature, salinity, and DO were represented in the range of 8.6–28.0 °C, 26.2–33.6 psu, and 4.9-8.9 mg L^{-1}, respectively, with no significant spatial variation within the five sampling sites (Fig. [2](#)). The
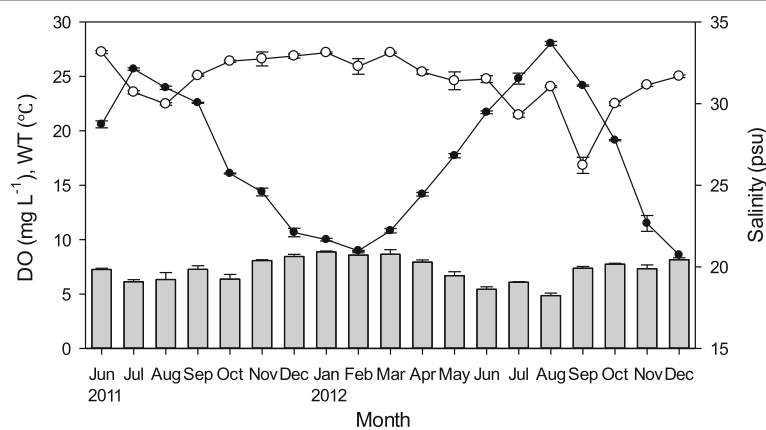

Fig. 2 Monthly variations in water temperature (●), salinity (○), and dissolved oxygen (vertical bars) in the waters of the study site. The reported values represent the mean and standard deviation from the five sampling stations

maximum water temperatures in the summer off the Wando coast were low compared with those off the Tongyeong coast, which is well known for oyster culturing, and this temperature difference might be attributed to a strong tidal front around Jindo island (Jung 2001; Moon et al. 2006; Oh et al. 2008).

Precipitation can influence the success of oysters (Calvo et al. 1999; Soletchnik et al. 2007), and the input of freshwater can increase PP in coastal waters by the input of land-driven nutrient into the coastal region (Choi et al. 1997). However, no significant regression was observed between salinity and precipitation ($P > 0.05$) in the present study, which indicates that rainfall is not the main contributor of nutrients to the studied waters. The relatively consistent salinity (30–33 psu) might be influenced by the input of freshwater from adjunct land areas.

The major source of freshwater near the study site is effluent from the tidal gate at Doam-myeon, located ~ 24 km north of the study area. An analysis of tidal residual flow indicates that the effluent from the tidal gate flows mainly out toward Deukryang Bay (Lee and Park 2006), which is located across the channel between Gogeum Island and Maryang-myeon in Gangjin-gun. This flow pattern of the effluent could prevent an abrupt change in salinity after a large rainfall event, which could cause a mass mortality of the rack oyster cultures. The tide with the greatest channel influence on the study area comes from the channel located between Gunwe-myeon in Wando and Pukpyeong-myeon in Haenam-gun, and this waster is weakly mixed with the tide from the Doam effluent between Goma and Sahoo Island.

No clear spatial pattern was observed in the concentration of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphate (DIP) at the sampling stations located in the seawater surrounding the oyster farm. The measured values were in the range of 0.014-0.062 mg L^{-1} for NH_4-N, 0.001–0.007 mg L^{-1} for NO_2-N, 0.104–0.355 mg L^{-1} for NO_3-N, and 0.011-0.025 mg L^{-1} for DIP. A seasonal change was observed in nitrate, DIN, and DIP, with a slightly higher concentration in spring and summer than in winter (Fig. 3).

The nitrogen content of the water at surrounding sites was not clearly influenced by precipitation or seasonality (Table 1), which indicated that nitrogen input into this area was weak and relatively consistent. This result could be attributed to the mineralization of resuspended sediment. Resuspension of sediment can double the mineralization rates compared with sediments that are not subjected to turbulence water, regardless of turbulence interval between the events (Ståhlberg et al. 2006). The studied oyster farm is located in the intertidal zone off the Wando coast where the water depth is only 2-3 m at high tide. The sediment could easily be resuspended into the water column by even mild wind and the occasional passing of ships. This resuspension of the sediments might be a source of additional nutrient supply in the waters of the study area. A relatively high tidal current might also contribute to the resuspension of the sediments. The maximum tidal current in the study area is 28.1–29.1 cm s^{-1} during high tide (Whan et al. 2003; Cho et al. 2013b). This current, combined with increased wave action from various potential sources such as passing ships or wind (Carlin et al. 2016), could be enough to generate sediment resuspension and subsequent mineralization of the sediments.

Chlorophyll-a content in the study area ranged from 0.31 to 10.46 μg L^{-1}, with an average mean of 2.06 ± 2.10 μg L^{-1}, and was characterized by high temporal variation but no spatial variation ($P > 0.05$). Peak phytoplankton blooms were observed in the spring and autumn of 2012. The estimated PP ranged from 17.1 to 1052.5 mgC m^{-2} day^{-1}, with an average of 204.2 ± 224.8 mgC m^{-2} day^{-1}; however, with the exception of times of intense phytoplankton blooms, the PP was usually below 200 mgC m^{-2} day^{-1} (Fig. 4). The trends in PP in this region are similar to those at Gosung Bay on the southern coast and Garorim Bay on the west coast of South Korea (Cho 2013). However, the estimated PP is lower than the values reported for Pukman Bay (Jeong et al. 2009), Gosueng Bay (Lee et al. 2016), Hansan-Geoje Bay (Park et al. 2002), and Kamak Bay (Cho et al. 1996), all oyster farming region off the southern coast of South Korea. The variations in PP in the study area are more similar to those observed off the western coast than the southern coast of South Korea. Primary production is relatively low off the southern coast of South Korea, with reported values below 200 mgC m^{-2} day^{-1} throughout the year except during spring and autumn, when phytoplankton blooms generally occur. High turbidity, due to shallow water depth and strong tidal current, could have limited the photosynthetic efficiency of the primary producers in this region (Kuehl and Troelstrup 2013). However, during high tide, the currents could contribute an additional input of chlorophyll-a by freeing benthic diatoms from the sediment (Joint and Pomroy 1981). In the present study, microscopic examination of the phytoplankton composition indicates that benthic diatom species such as *Paralia sulcata* (Cho et al. 2013b) were relatively scarce. The absence of spring and autumn phytoplankton bloom has been reported to be a distinct feature of waters with high turbidity (Al-Hasan et al. 1975; Joint and Pomroy 1981; Cho 2013); however, the obvious spring and autumn blooms might be attributed to the direct or indirect influence of freshwater input from the adjacent basin and effluent from Doam-myoen at Gangjin-gun.

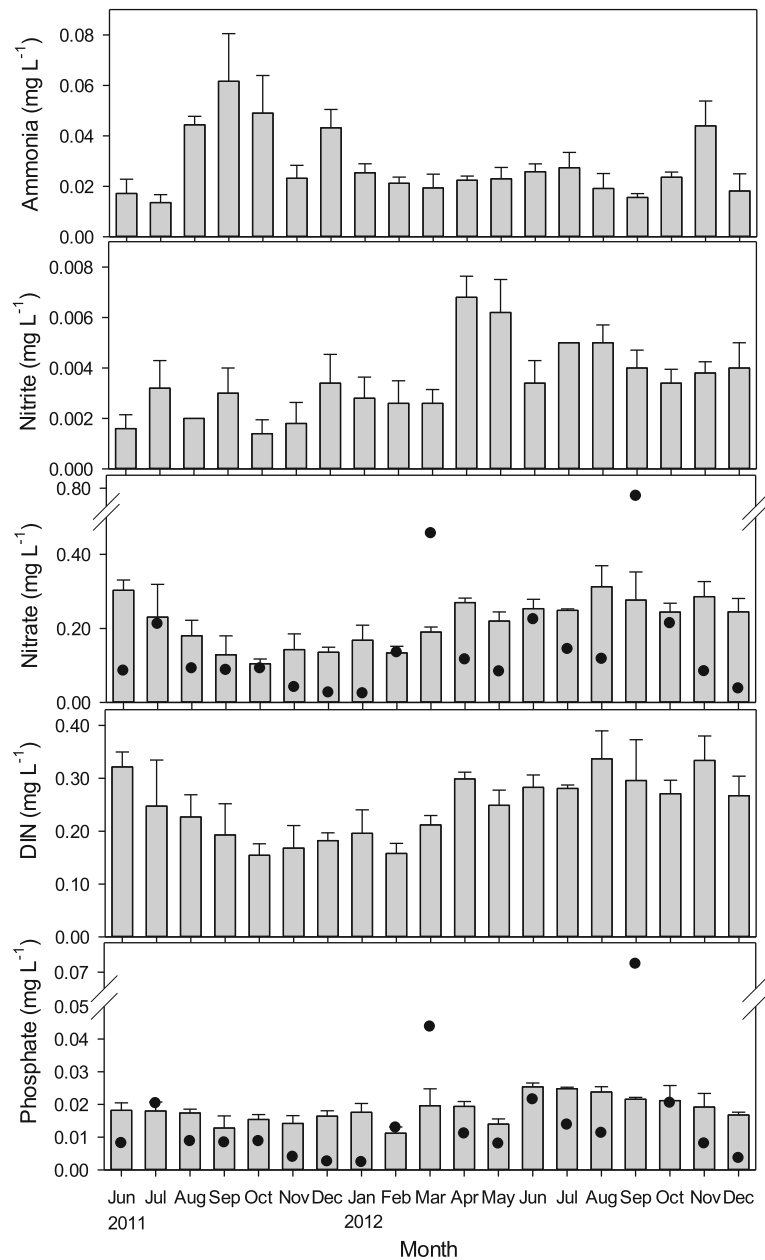According to the generalized equation for photosynthesis reported by Odum (1971), the availability of

Fig. 3 Monthly variations in nutrients at the studied sites. Closed circle (●) indicate the estimated demand for primary production according to Odum (1971). Temporal limitations in nutrient availability were observed for both nitrate and phosphate concentrations

Table 1 Pearson correlations coefficients between water qualities

	Salinity	DO	NH₄-N	NO₂-N	NO₃-N	DIN	DIP
WT	− 0.587*	− 0.822**	− 0.0303	0.120	0.389	0.419	0.479*
Salinity		0.365	0.147	− 0.311	− 0.416	− 0.427	− 0.448
DO			− 0.051	− 0.181	− 0.387	− 0.438	− 0.503*
NH₄-N				− 0.255	− 0.533*	− 0.362	− 0.320
NO2-N					0.505*	0.517*	0.323
NO3-N						0.982**	0.702**
DIN							0.699**

*P < 0.05; **P < 0.01

nitrate and phosphate for primary production was temporarily limited during the spring and autumn blooming season (Fig. 3). The nutrient availability was limited to a much greater degree in 2012 than in 2011. The hydrodynamic and geological features of this region contribute to the low availability of nutrients in these wasters. The majority of freshwater from the discharge of tidal gate was mostly flowed out toward Deukrayng Bay, meaning that most land-derived input of freshwater in this region consists of runoff, stream water, and hatchery discharge. However, the nutrient load of
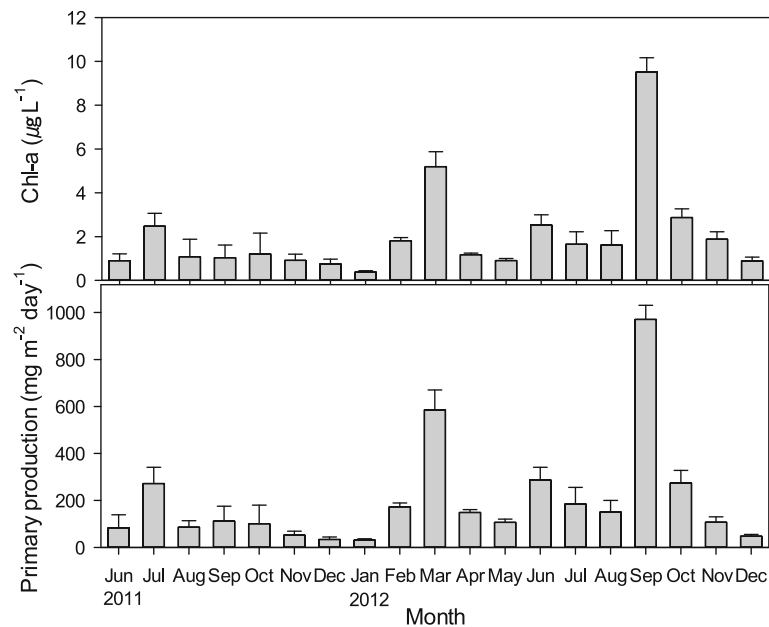
Fig. 4 Monthly variations in chlorophyll-a and primary production in the waters of the study area

adjacent basin did not significantly affect the water quality in the study area, as the pollution load showed half dilution within a radius of 300 m (Kang et al. 2015).

Conclusion

Despite the studied waters being located in semi-enclosed ria coast surrounded by several islands, hydrodynamic and geological features make the waters in this area favorable to oyster farming with relatively higher PP. Sediment resuspension might contribute nutrients input that enhance primary production, which satisfied the nutrient demand during the times when phytoplankton blooming are absent; however, during the spring and autumn when phytoplankton blooms occur, this process cannot provide sufficient nutrients for PP due to insufficient nutrient input from the adjacent basin and terrestrial sources.

Abbreviations
ANOVA: Analysis of variance; DIN: Dissolved inorganic nitrogen; DIP: Dissolved inorganic phosphorus; DO: Dissolved oxygen; MSY: Maximum sustainable yield; PP: Primary production

Availability of data and materials
Not applicable

Authors' contributions
WGJ and SMC designed the study. WGJ carried out the model for primary production. SMC carried out the field survey and drafted the manuscript. Both authors read and approved the final manuscript.

Ethics approval
Experimental protocols followed the guidelines of the Animal Care and Use Committee of Kunsan National University.

Consent for publication
Not applicable

Competing interests
Both authors declare that they have no competing interests.

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Author details
[1]Department of Seafood and Aquaculture Science, Gyeongsang National University, Tongyeong 650-160, Korea. [2]School of Applied Marine bioscience, Kunsan National University, Gunsan 573-701, Korea.

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