ARTICLE

Evaluation of Ecosystem Services Provided by Pacific Oyster, *Crassostrea gigas*, Farms in Hansan Bay, Korea

Jongyoon Baek[1] · Seonggil Go[1] · Jungho Nam[2] · Kwang-Sik Choi[1] · Sukgeun Jung[1]

Abstract

Korea is the second highest producer of cultured Pacific oyster, *Crassostrea gigas*, in the world, but their potential economic values of ecosystem services have not yet been evaluated. As the first case study, we evaluated the potential values of *C. gigas* cultured in Hansan Bay, Korea. We utilized Gangnery's growth model to assess the provisioning and regulating services, assuming that the nitrogen removal amount equals the difference between input and harvested oysters in terms of accumulated nitrogen. To convert these measured services into monetary values, we used the market price of *C. gigas* for provisioning service, and the annual operational report regarding the current state of domestic sewage treatments for regulating service. We estimated that cultivating a ha of *C. gigas* farms has a monetary value ranging from ca. −16.6 to 67.6 thousand US dollars, which is considerably lower than other research findings. Results suggested that the growth model applied in this study is suitable and effective, particularly in cases where other models may not be applicable. Additionally, we compared the values of coastal areas when shifting from *C. gigas* cultivation to another species or maintaining the status quo to assist policymakers in making decisions. Despite some limitations, our model is expected to contribute to appraising the monetary values of coastal areas and mitigating conflicts in marine spatial planning.

Keywords Marine spatial planning · Ecosystem services · Shellfish aquaculture · Shellfish growth model

1 Introduction

The global production of aquaculture has steadily increased during the past two decades, and it presently accounts for > 50% of the fish food supply (Fig. 1; Aksnes et al. 2017; Botta et al. 2020; FAO 2022). Specifically, the production of mollusks has seen a significant increase, with the Pacific oyster, *Crassostrea gigas*, emerging as the leading species (Aksnes et al. 2017; FAO 2022).

C. gigas live in water with temperatures of 4–24 ℃ around intertidal or shallow subtidal areas (Shatkin et al. 1997). They primarily consume phytoplankton and detritus in the water column, directly. *C. gigas* was globally introduced for aquaculture due to its rapid growth and high productivity (Shatkin et al. 1997; Harris 2008;). In Korea, *C. gigas* is typically hardened before cultivation to prevent mass mortality (Park et al. 1988). However, *C. gigas* cultured on farms often suffer from summer mortality syndrome, which leads to mass killing (Koganezawa 1975). The exact causes of the syndrome remain unclear, but several potential causes including hypoxia, over-maturation, and the emergence of new disease outbreaks have been proposed (Han et al. 2013).

C. gigas contribute to human well-being in various ways. First, they can supply food sources to humans. In 2020, ca. 6×10^6 tons of *C. gigas* were produced, accounting for ca. 8% of the total global production from aquaculture (FAO 2022). Second, oyster species can mitigate eutrophication

✉ Sukgeun Jung
sukgeun.jung@gmail.com

Jongyoon Baek
jongyoon1993@gmail.com

Seonggil Go
seonggil117@gmail.com

Jungho Nam
jhnam@kmi.re.kr

Kwang-Sik Choi
skchoi@jejunu.ac.kr

[1] Department of Marine Life Science, Jeju National University, Jeju 63243, Republic of Korea

[2] Marine Policy Research Department, Korea Maritime Institute, Busan 49111, Republic of Korea

Fig. 1 Global aquaculture production by major taxonomic groups reported in the FAO (2022)
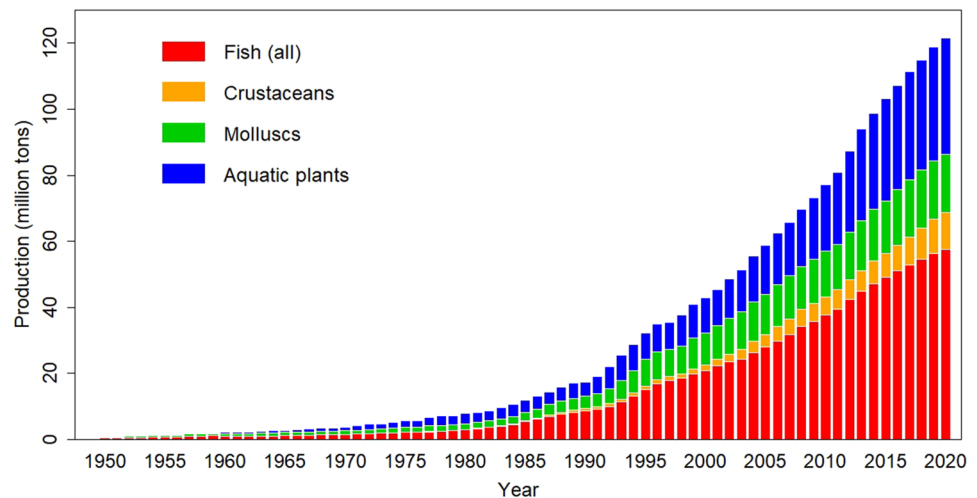
by removing nitrogen from the water column by consuming phytoplankton and detritus, thereby helping maintain water quality (Newell et al. 2005). Newell et al. (2005) estimated that the eastern oyster, *Crassostrea virginica*, reefs remove ca.13,080 kg of nitrogen, corresponding to 314,836 US dollars (USD), in the Choptank River, Maryland, USA. Ferreira et al. (2007) estimated that net nitrogen removal was almost 10.7 tons per year from 0.6 ha (100×100 m^2) of oyster farms, equivalent to the total amount of nitrogen in untreated sewage discharged by 3237 people. Last, oysters provide supporting services to marine ecosystems. Their reefs serve the habitats for other marine species and can increase fish production (Peterson et al. 2003). Oyster shells, separated from oyster reefs, stabilized sediment and reduced the wave energies affecting the erosion of salt marsh fringes (Meyer et al. 1997). Furthermore, oyster reefs can protect coastal areas against rising sea levels caused by global warming (Coen et al. 1999; Piazza et al. 2005). These benefits are called "ecosystem services" (Ehrlich and Ehrlich 1981).

Korea is the second biggest producer of cultured *C. gigas* (ca. 300,084 tons in 2020) following China (FAO 2022). However, Korea's interest in cultured *C. gigas* has primarily focused on its role in the food supply, overlooking its other functions. This approach has impeded the proper evaluation of the coastal ecosystem, leading to confusion and conflicts in coastal development planning (Choi 2008).

Here, we evaluated the ecosystem services provided by cultured *C. gigas* for the first time in Korea to assist policymakers in making decisions on marine spatial planning. For this purpose, we developed a bio-economic model that evaluates the ecosystem services based on the production and total amount of nitrogen accumulated by the *C. gigas*.

2 Material and Methods

2.1 Study Area

We chose Hansan Bay to evaluate the ecosystem services provided by the *C. gigas* because the coverage of the farm area (ca. 26%) is higher than in other bays (ca. 4.7% on average) (National Federation of Fisheries Cooperatives 2023). Korea has predominantly used the submerged long-line method for culturing *C. gigas* since the 1960s, accounting for ca. 98% of the total oyster production (ca. 300,840 tons in 2020). This method is practiced offshore and applied to large-scale aquaculture. The long lines, made of light materials, float on the sea surface to hold the submerged lines to which oyster spats are attached (Aldon 1998). The water depth in the bay ranges from 6.5 to 27.9 m, and the monthly mean water temperatures range from 9.0 to 25.6 °C, with monthly mean salinities ranging from 29.5 to 34.2 (Park et al. 2016). Cultivation of *C. gigas* in Hansan Bay typically is operated from May to the following February in the area of 542 ha (Kang et al. 2000; National Federation of Fisheries Cooperatives 2023).

2.2 *C. gigas* Production in Hansan Bay

To estimate the production of *C. gigas* in Hansan Bay, we first tried to estimate the initial oyster population by multiplying the number of oysters per spat collector, ca. 50, with the count of spat collectors per longline, which varies between 5000 and 7500. Additionally, multiplying this

with the number of longlines per ha of farms, typically ca. 20 (NFRDI 2012; Han et al. 2013; Lee et al. 2018; Oh et al. 2002). The derived initial oyster population ranged from ca. 5 to 7.5 million individuals per ha of farms.

To estimate the growth performance of *C. gigas*, we adopted the growth model developed by Gangnery et al. (2003). The model is as follows:

$$G_t = a \times F_t^b \times T_t^c \times Y_t^d, \tag{1}$$

$$TW_H = TW_I + \sum_{t=1}^{\text{Cultivation period in Months}} G_t, \tag{2}$$

where G_t is the growth in grams per month, F_t is food concentration in micrograms per liter, T_t is the water temperature (°C), TW_t is an individual dry tissue weight in grams, TW_H is a harvested individual's dry tissue weight in grams, TW_I is an initial individual's dry tissue weight in grams, and t is the month in the cultivation period. The parameters "*a*," "*b*," "*c*," and "*d*" were estimated through non-linear regression using R software, and the data of the variables were obtained from a past study that reported the growth of *C. gigas* and environmental conditions during the cultivation periods of 2008 and 2013 in Hansan Bay (Lee et al. 2018). For F_t, we used the concentration of chlorophyll-a, which represents the biomass of phytoplankton. This was based on a previous study that indicated phytoplankton as the primary food source for oysters, confirmed through stable isotope analysis (Langdon and Newell 1996).

To account for the mortality of *C. gigas* during cultivation, we assumed that the accumulated mortality rates of *C. gigas* range from 20 to 95%, taking into account the summer mass mortality event (Han et al. 2013; Hong et al. 2022; Koganezawa 1975; Luna-González et al. 2008). With these assumptions, we calculated the initial biomass and harvested biomass of *C. gigas* using the equations as follows:

$$B_I = TW_I \times PPO_I \tag{3}$$

$$B_H = TW_H \times PPO_I \times M_a \tag{4}$$

where B_I is the initial biomass of *C. gigas* from farms in tons, B_H is the harvested biomass of *C. gigas* from farms in tons, PPO_I is the initial population of *C. gigas* cultured on farms in individuals, and M_a is the accumulated mortality rate of cultured *C. gigas*. Calculating the difference between B_H and B_I, we determined the cultured *C. gigas* production.

2.3 Provisioning and Regulating Services provided by cultured *C. gigas* in Hansan Bay

C. gigas is mainly cultured using the long-line method in Hansan Bay, making it difficult to offer oyster shells to coastal areas to prevent erosion of sediment caused by the tide. Therefore, we only evaluated the provisioning and regulation services provided by the *C. gigas,* excluding the supporting service.

To evaluate the provisioning service, we investigated the domestic market prices of *C. gigas*. According to the Korean Statistical Information Service (2022), the total market price and amount of oyster production, including shell weight, was *ca.* 305,614 tons and 214.88 million USD in 2021. They estimated the values based on the wet weight of *C. gigas*, including shell weight. As our growth model estimated the dry tissue weight of *C. gigas*, we assumed the ratio of dry weight to wet weight is 0.2, adjusted the total weight to the tissue weight using Eq. 5, and evaluated the market price using Eq. 6 as follows (Hyun et al. 2001; Shim et al. 2021):

$$pTW = -0.0559 \times \text{Year} + 128.29 \tag{5}$$

$$\text{The domestic market price of a ton of } C.gigas = \frac{214.88 \text{ million USD}}{pTW \times 305,614} \tag{6}$$

where pTW refers to the proportion of tissue weight in the total wet weight of *C. gigas*. By multiplying the result of Eq. 6 and the *C. gigas* production estimated from Eqs. 3 and 4, we calculated the monetary value of the provisioning service provided by cultured *C. gigas* in Hansan Bay.

Before evaluating the regulating services provided by *C. gigas*, we needed to estimate the amount of nitrogen removal by *C. gigas*. We assumed that the amount of nitrogen removed by cultured *C. gigas* equals the difference in accumulated nitrogen between the B_I and B_H. Here, we only considered nitrogen accumulation rates in the tissues because, in cultivation, *C. gigas* typically settle on empty shells prepared by farmers and do not invest in shell development. Based on a past study, we assumed that the nitrogen accumulation rate accounts for 7.85% of the dry tissue weight of *C. gigas* (Schatte Olivier et al. 2018). The derived equation is as follows:

Amount of nitrogen removed by cultured
$$C.gigas = 7.85\% \times (B_H - B_I). \tag{7}$$

Beseres Pollack et al. (2013) previously estimated the monetary value of regulation services provided by *C. gigas* using the cost of sewage treatments. Building upon this approach, we evaluated the regulation service provided by cultured *C. gigas* in Hansan Bay and assumed that they fully replace the denitrification process in sewage treatments. We focused on three types of sewage treatments mainly used in Korea for eliminating nitrogen through denitrification (Ministry of Environment 2019): Anaerobic–anoxic–aerobic method (A2O), modified Kist Shinwon Biological Nutrient Removal (KSBNR), and modified Ludzack Ettinger

(MLE). To evaluate the effectiveness of these treatments, we assumed the annual operational cost of removing nitrogen per m³ of sewage treatments to be ca. 73.6 USD, the total volume of sewage treatments to be 0.424×10^6 m³, the annual amount of nitrogen removed by 1 m³ of sewage treatments to be ca. 7.36 kg, the total cost of constructing sewage treatments to be 534.6 million USD, and the life span of sewage treatments to be ca. 20 years (15–20 years), based on the reports by the Ministry of Environment (2019). To estimate the monetary value of the annual regulation service provided by cultured *C. gigas*, we used the following equations:

$$\text{dcST}_{\text{annual}} = \frac{\text{cCST}_{\text{total}}}{\text{lsST} \times \text{vST}_{\text{total}}}. \tag{8}$$

The cost for removal of 1 kg of nitrogen through sewage treatments

$$= \frac{\text{dcST}_{\text{annual}} + \text{ocNR}_{\text{annual}}}{\text{aNR}_{\text{annual}}}, \tag{9}$$

where $\text{dcST}_{\text{annual}}$ is the annual depreciable cost for a ton of sewage treatment, $\text{cCST}_{\text{total}}$ is the total cost of constructing sewage treatments in USD, lsST is the life span of sewage treatments, $\text{vST}_{\text{total}}$ is the total volume of sewage treatments, $\text{aNR}_{\text{annual}}$ is the annual amount of nitrogen removed per m³ of sewage treatments, and the $\text{ocNR}_{\text{annual}}$ is the annual operational cost of removing nitrogen by 1 m³ of sewage treatments. We calculated the annual depreciable cost per m³ of sewage treatment to be 62.9 USD using Eq. 8. Considering the annual depreciable cost, we calculated that ca. 18.55 USD is incurred annually for the removal of 1 kg of nitrogen through sewage treatments using Eq. 9. By multiplying the results of Eqs. 7 and 9, we calculated the monetary value of regulation services provided by *C. gigas* farm.

3 Results and Discussions

3.1 *C. gigas* Production in Hansan Bay

The derived growth equation (Eq. 1) was as follows:

$$G_t = 76.4240 \times F_t^{0.2462} \times T_t^{-2.2619} \times Y_t^{-0.8701}.$$

The estimated dry weight of a harvested individual of *C. gigas* ranged from ca. 1.502 to 2.051 g in 2009 and from ca. 1.456 to 2.004 g in 2014. All observed dry weights of an individual of *C. gigas* in 2008 were within the 95% confidence interval, except in October and November 2013 (Fig. 2a and b). Applying the results of Eqs. 1 to 3 and 4, we estimated that the production of *C. gigas* in Hansan Bay ranged from ca. – 710 to 6070 tons of dry tissue weight in 2009 and from ca. – 1492 to 5136 tons of dry tissue weight in 2014.

We validated our growth model by comparing it with the Scope for Growth (SFG) model applied to Hansan Bay in a previous study (Lee et al. 2018). Our results indicated that, during the period of 2008, Gangnery's growth model ($r^2 = 0.991$) was more suitable than the SFG model ($r^2 = 0.984$). However, during the period of 2013, the SFG model ($r^2 = 0.971$) was more suitable than Gangnery's growth model ($r^2 = 0.861$). Our findings indicate that Gangnery's growth model is as reliable as the SFG model in estimating the dry tissue weights of *C. gigas* during cultivation, because of no significant difference in comparison with observed dry tissue weights (Fig. 2a and b). This suggests that Gangnery's growth model alone is sufficient for estimating growth when food consumption data are unavailable (Tables 1, 2).

3.2 Provisioning and Regulating Services provided by cultured *C. gigas* in Hansan Bay

Using Eqs. 5 and 6, we estimated that the pTW was ca. 15.3, and the domestic market price of a ton of *C. gigas* was ca. 4586 USD in 2021. Multiplying with *C. gigas* production in Hansan Bay, we estimated that the monetary value of provisioning services ranged from ca. −3260 to 27,839 thousand USD in 2009 and from ca. – 6845 to 23,552 thousand USD in 2014. The estimated monetary value of the regulation service in Hansan Bay ranged from ca. – 1035 to 8839 thousand USD in 2009 and from ca. – 2173 to 7478 thousand USD in 2014 using Eqs. 7 and 9. The results indicate a decline in monetary value in 2014 compared to 2009. This decline was attributed to a decrease in the growth performance of *C. gigas* in 2014 (ca. two- to threefold increase in initial weight) compared to 2009 (ca. five- to sevenfold increase in initial weight). Considering the surface area of farms in Hansan Bay, cultivating a ha of *C. gigas* farms has a potential value ranging from ca. – 16.6 to 67.6 thousand USD.

To validate our evaluation of the monetary value of the regulation service, we compared our estimate with past studies in USD per kg of nitrogen removal. Our estimate (ca. 18.55) was slightly lower than that of Newell et al. (2005) (ca. 24.07), but much lower than an estimate from Ferreira et al. (2007) that adopted the Farm Aquaculture Resource Management (FARM) model (ca. 206.11).

The discrepancy between our and the FARM models may be attributed to several factors. First, the FARM model estimated that a ha of oyster farms removes ca. 3 tons of nitrogen, significantly greater than our estimates, ca. – 0.216 to 0.879 tons. The FARM model was developed based on the polyculture method known as integrated multi-trophic aquaculture (IMTA), where the various species are cultured together. Reid et al. (2013) and Chopin et al. (2010) documented the advantage of IMTA regarding

Fig. 2 The dry tissue weights of *C. gigas* were measured in two periods, 2008–2009 (**a**) and 2013–2014 (**b**), in Hansan Bay, Korea. The red triangles on a dashed red line denote the dry tissue weights estimated by Gangnery's growth model, with 95% confidence intervals. The black circles on a black line denote the dry tissue weights estimated by the Scope for Growth model, and the blue crosses the observed dry tissue weights
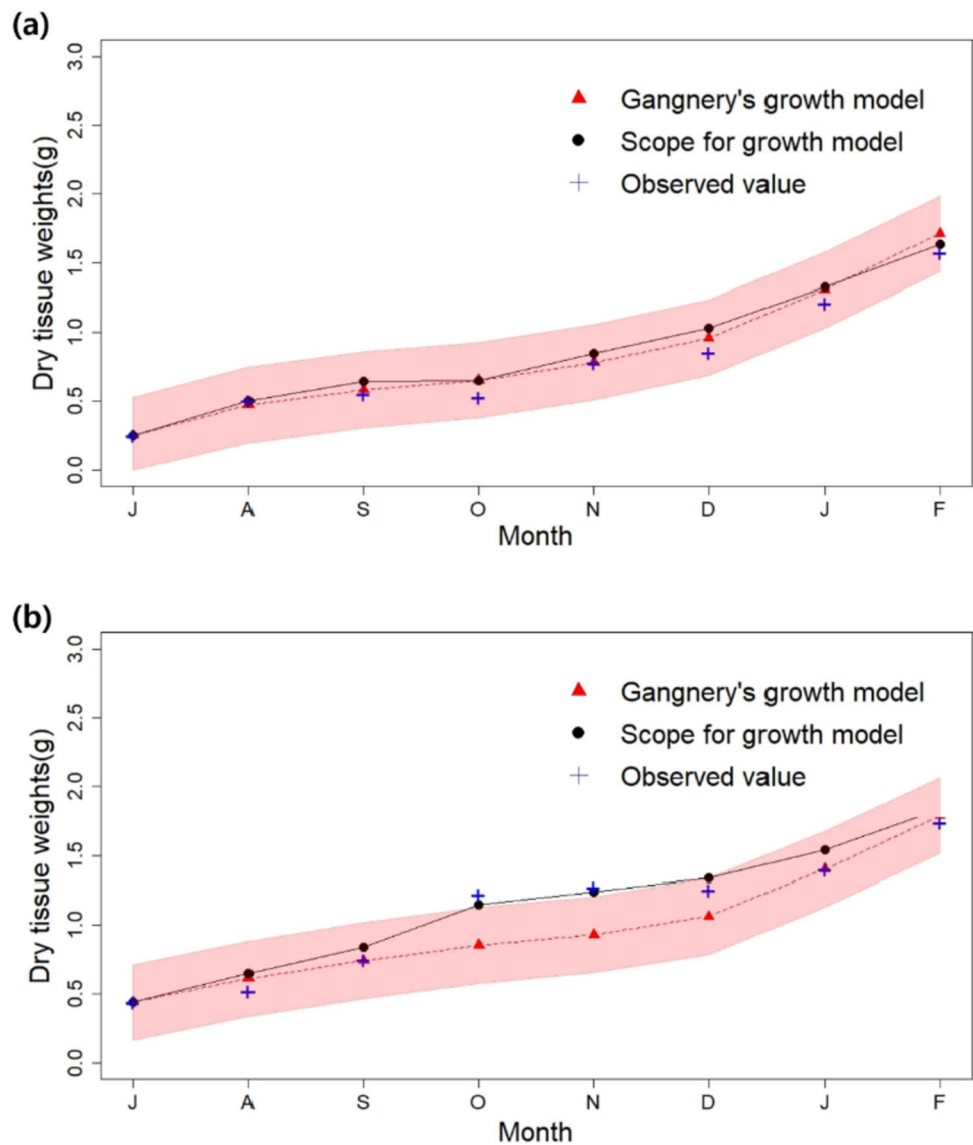
Table 1 Accumulated mortality rates of cultured *C. gigas* reported by past studies

Accumulated mortality rate (%)	Reference
50–60	(Koganezawa 1975)
70	(Luna-González et al. 2008)
80–90	(Han et al. 2013)
11.3–33.3	(Hong et al. 2022)

oxygen concentration and food supplies. In contrast, *C. gigas* in Korea are typically cultured using intensive monoculture, making them more vulnerable to hypoxia and food limitation, which lead to a decline in oyster production (Park et al. 2018). Second, while our model assessed the monetary value directly from the estimated nitrogen removal in kg, the FARM model utilized the sewage treatment costs per inhabitant and assumed the annual amount of nitrogen emitted by a person in the evaluation (Galvao et al. 2005). These differences may explain, at least partially, the discrepancies.

3.3 Comparison with Alternative Species

According to the Korean Statistical Information Service (2022), Korea produced ca. 16,000 tons of Korean rockfish, *Sebastes schlegelii*, using cage culture, which corresponds to ca. 149 million USD. In 2021, the total area of cage culture in Korea was 98 ha, in which the cage culture of *S. schlegelii* accounted for ca. 53.8 ha. To compare with the value of *C. gigas* farms, we evaluated and assumed that the cost of feed was ca. 2,782 thousand USD per ha of cage culture for *S. schlegelii.* At first glance, it appears that cage cultures of *S. schlegelii* are more valuable than *C. gigas* farms (ca. – 16.6–67.6 thousand USD per ha). However, Korea is

Table 2 The chemical compositions of oysters

Species	Carbon (Tissue)	Nitrogen (Tissue)	Carbon (Shell)	Nitrogen (Shell)	Reference
Crassostrea gigas	–	8.4	–	–	(Ren et al. 2003)
Crassostrea gigas	44.9	8.19	11.52	0.12	(Zhou et al. 2002)
Crassostrea gigas	–	7.4	–	–	(Linehan et al. 1999)
Crassostrea virginica	44.72	7.72	12.17	0.2	(Higgins et al. 2011)
Crassostrea virginica	–	7.54	–	–	(Sidwell et al. 1973)
Oyster mean (± 1 SE)	44.81 ± 0.09	7.85 ± 0.19	11.85 ± 0.33	0.16 ± 0.04	(Schatte Olivier et al. 2018)

planning to substitute formula feed (ca. 1.5 USD per kg) for raw feed (ca. 0.37 USD per kg) to manage the marine ecosystem. We estimated that replacing raw feed with formula feed will cause a loss of ca. 850 thousand USD per ha, because of the difference in the feed efficiency (Myeong et al. 1997). Despite the advantage of *S. schlegelii* in commercial value, environmental concerns suggest that *C. gigas* will be more preferable than *S. schlegelii* for cage culture.

3.4 Supporting Decisions in Compensation for Disasters and Development

The Korean government provides compensation to aquaculture entrepreneurs who lose more than 50% of their fish and shellfish by disaster, accident, and development. The most common example of a disaster that affected this industry is an oil spill, for which International Oil Pollution Compensation (IOPC) Funds compensate. The IOPC Funds calculate financial losses by comparing production before and after oil damage. Similarly, the Korean government determines the compensation amount for developments based on the business results of the past three years and land prices (Jang 2005).

However, relying solely on past business results may not always accurately reflect future earnings. Therefore, a clear and transparent method is required for calculating, as it can affect the livelihoods of workers in affected industries. Our model is expected to provide a more comprehensive approach to determining financial losses and compensation amounts by estimating future earnings.

4 Problems, Limitations, and Future Works of the Study

While our growth model is well suited for estimating the growth of *C. gigas* in Hansan Bay, its applicability in other regions is still uncertain. Because we developed the model based on specific parameters from Hansan Bay, it may not accurately reflect conditions in other areas. To address

this, we need to improve the model for other regions. The most effective method for enhancing the model is to collect extensive growth data of *C. gigas* cultured in various regions. The model's parameters were calculated based on observed weight values using non-linear regression. This implies that incorporating numerous observed data from different environmental factors and periods will enhance the reliability of the model's parameters, resulting in more realistic predictions on the growth of oysters in Korea.

Our approach to estimating nitrogen removal considers only the amount of nitrogen assimilated in the tissue of *C. gigas* and the nitrogen removed from the marine ecosystem through the harvest of *C. gigas*, which is called *"bioextraction"* (Donnelly et al. 2023). However, *C. gigas* remove nitrogen from the water column in more complicated ways. Donnelly et al. (2023) illustrated the ecological process associated with oysters that improve water quality by removing nitrogen, showing that the *C. gigas* produced *"biodeposits"* such as feces, which stimulate denitrification in marine ecosystems. In addition, they documented the various factors that influence the ability of oysters to remove nitrogen. Our approach currently has limitations in considering such factors. Furthermore, in evaluating regulation service, we didn't consider the salvage value derived from sewage treatments due to the lack of empirical cases. Therefore, we plan to develop the nitrogen removal model by considering all of the pathways by which *C. gigas* removes nitrogen when empirical cases regarding salvage value for the sewage treatments are available.

Our analysis suggested that the monetary value of ecosystem services provided by *C. gigas* in Hansan Bay is highly dependent on the assumed mortality rates of oysters, leading to great variability and uncertainty in the estimates. Past studies have mostly reported the mortalities of cultured *C. gigas* as accumulated mortalities, because oysters cultured by the long-line method were submerged until harvest, making it difficult for researchers to estimate the monthly mortalities. Therefore, we could not consider

the monthly variation in mortality. To provide a more accurate and reasonable estimation, we need to cooperate with oyster farm industries in Korea to estimate monthly mortalities of cultured *C. gigas* in future studies.

5 Conclusions

We have developed a bio-economic model to evaluate the ecosystem services provided by cultured *C. gigas* in Hansan Bay. Our results indicated that Gangnery's growth model, employed for estimating oyster growth, is a suitable replacement for other growth models in cases where food consumption data are limited. Additionally, we found that the nitrogen removal model can be applied when a growth model of oysters is available. However, our results suggest that the potential value offered by *C. gigas* in Hansan Bay is much lower compared to other sites where IMTA is used for cultivation. This finding implies that IMTA may be a more suitable method for culturing *C. gigas* in terms of the regulating services provided by *C. gigas*. Such insights may have some limitations, but we expect that our approach and methods will provide a useful foundation for future studies and applications to assist policymakers in making decisions between conservation and development, and in determining financial compensation for disaster, accident, and development in coastal and oceanic areas.

Data availability All data used in this manuscript are opened to the public and referred in References.

References

Aksnes DL, Holm P, Bavinck M, Biermann F, Donovaro R, Harvey P, Hynes S, Ingram J, Kaiser M and Kaushik S (2017) Food from the Oceans-how can more food and biomass be obtained from the oceans in a way that does not deprive future generations of their benefits? Science Advice for Policy by European Academies (SAPEA), p 14

Aldon ET (1998) The different ways to grow oysters and mussels. Asian Aquacult 20(4):14–15

Beseres Pollack J, Yoskowitz D, Kim H, Montagna PA (2013) Role and value of nitrogen regulation provided by oysters (*Crassostrea virginica*) in the Mission-Aransas Estuary, Texas, USA. PLoS ONE 8(6):e65314. https://doi.org/10.1371/journal.pone.0065314

Botta R, Asche F, Borsum JS, Camp EV (2020) A review of global oyster aquaculture production and consumption. Mar Policy 117:103952. https://doi.org/10.1016/j.marpol.2020.10395

Choi K (2008) Oyster capture-based aquaculture in the Republic of Korea. capture-based aquaculture. Glob Rev FAO Fish Tech Pap 508:271–286

Chopin T, Troell M, Reid GK, Knowler D (2010) Integrated multi-trophic aquaculturea - a responsible practice providing diversified seafood products while rendering biomitigating services through its extractive components. In: Chopin T (ed) Advancing the aquaculture agenda. OECD Publishing, Paris, pp 195–217

Coen LD, Luckenbach MW, Breitburg DL (1999) The role of oyster reefs as essential fish habitat: A review of current knowledge and some new perspectives. In: American fisheries society symposium. pp 438–454

Donnelly H, Smyth A, Baker S, Reynolds L, Collins A (2023) How do oysters remove nitrogen? EDIS. https://doi.org/10.32473/edis-ss711-2023

Ehrlich PR, Ehrlich A (1981) Extinction: the causes and consequences of the disappearance of species. Random House, New York, p 305

FAO (2022) Fishery and aquaculture statistics. Global aquaculture production 1950–2020 (FishStatJ). https://www.fao.org/fishery/en/topic/166235?lang=en Accessed 15 Sep 2022

Ferreira JG, Hawkins AJS, Bricker SB (2007) Management of productivity, environmental effects and profitability of shellfish aquaculture — the farm aquaculture resource management (FARM) model. Aquaculture 264(1):160–174. https://doi.org/10.1016/j.aquaculture.2006.12.017

Galvao A, Matos J, Rodrigues J, Heath P (2005) Sustainable sewage solutions for small agglomerations. Water Sci Tecchnol 52(12):25–32

Gangnery A, Chabirand J, Lagarde F, Le Gall P, Oheix J, Bacher C, Buestel D (2003) Growth model of the Pacific oyster, *Crassostrea gigas*, cultured in Thau Lagoon (Méditerranée, France). Aquaculture 215:267–290. https://doi.org/10.1016/S0044-8486(02)00351-4

Han J, Jo Q, Park Y, Park T, Lee D, Cho K (2013) A report on the mass summer mortalities of the farmed Pacific oysters, *Crassostrea gigas* and Bay scallops *Argopecten irradians* in the local waters of Goseong Bay, Korea. Korean J Malacol 29(3):239–244. https://doi.org/10.9710/kjm.2013.29.3.239

Harris J (2008) Pacific oyster, *Crassostrea gigas* (thunberg, 1793). Aquat Invasions 9(2):175–182

Higgins CB, Stephenson K, Brown BL (2011) Nutrient bioassimilation capacity of aquacultured oysters: quantification of an ecosystem service. J Environ Qual 40(1):271–277. https://doi.org/10.2134/jeq2010.0203

Hong H, Park H, Choi K (2022) Growth and reproduction of the Pacific oyster *Crassostrea gigas* cultured on tidal flat in *Hebei Spirit* oil spill area on the west coast of Korea four years after the accident. Front Mar Sci 9:880210

Hyun K, Pang I, Klinck JM, Choi K, Lee J, Powell EN, Hofmann EE, Bochenek EA (2001) The effect of food composition on Pacific oyster *Crassostrea gigas* (Thunberg) growth in Korea: a modeling study. Aquaculture 199(1–2):41–62

Jang D (2005) Alternative policy and actual state on compensation for fisheries damage by oil pollution. J Korean Soc Mar Environ Safe 11(1):61–70

Kang C, Park MS, Lee P, Choi W, Lee W (2000) Seasonal variations in condition, reproductive activity, and biochemical composition of the Pacific oyster, *Crassostrea gigas* (Thunberg), in suspended culture in two coastal bays of Korea. J Shellfish Res 19(2):771–778

Koganezawa A (1975) Present status of studies on the mass mortality of cultured oyster in Japan and its prevention. Proceedings of the third U.S.-Japan Meeting on Aquaculture, Tokyo, Oct 15–16, 1974

Korean Statistical Information Service (2022) Results of the fishery production survey in 2021. https://kosis.kr/statisticsList/statistics

ListIndex.do?vwcd=MT_ZTITLE&menuId=M_01_01. Accessed 15 Sep 2022

Langdon C, Newell RIE (1996) The Eastern oyster: *Crassostrea virginica* - digestion and nutrition in larvae and adults. In: Kennedy VS, Newell RIE, Eble AF, Leffler M, Harpe SR (eds) The Eastern oyster: *Crassostrea virginica*. University of Maryland Sea Grant Publications, College Park, pp 231–260

Lee Y, Han E, Wilberg MJ, Lee W, Choi K, Kang C (2018) Physiological processes and gross energy budget of the submerged longline-cultured Pacific oyster *Crassostrea gigas* in a temperate bay of Korea. PLoS ONE 13(7):e0199752. https://doi.org/10.1371/journal.pone.0199752

Linehan LG, O'connor TP, Burnell G (1999) Seasonal variation in the chemical composition and fatty acid profile of Pacific oysters (*Crassostrea gigas*). Food Chem 64(2):211–214. https://doi.org/10.1016/S0308-8146(98)00144-7

Luna-González A, de Jesús R-G, Campa-Córdova Á, Orduña-Rojas J, Valles-Jiménez R, Ruíz-Verdugo CA (2008) Seasonal variations in the immunological and physiological parameters of the Pacific oyster *Crassostrea gigas* cultured in Bahía de Macapule (Sinaloa, Mexico). Aquac Res 39(14):1488–1497. https://doi.org/10.1111/j.1365-2109.2008.02017.x

Meyer DL, Townsend EC, Thayer GW (1997) Stabilization and erosion control value of oyster cultch for intertidal marsh. Restor Ecol 5(1):93–99. https://doi.org/10.1046/j.1526-100X.1997.09710.x

Ministry of Environment (2019) Annual monitoring report of the current state of operation of public wastewater treatment facilities in South Korea. https://www.me.go.kr/home/web/policy_data/read.do?menuId=10263&seq=7605. Accessed 11 Dec 2023

Myeong JI, Pack SY, Chang YJ (1997) Effects of water temperature and feeding rate on growth and feed efficiency of Korean rockfish, Sebastes schlegeli. J Aquac 10:311–320

National Federation of Fisheries Cooperatives (2023) Distribution of oyster farms using submerged long-line in South Korea. http://www.oyster-suhyup.co.kr/cooperative/fishing.php. Accessed 15 Sep 2022

Newell RI, Fisher TR, Holyoke RR, Cornwell JC (2005) Influence of eastern oysters on nitrogen and phosphorus regeneration in Chesapeake Bay, USA. In: The comparative roles of suspension-feeders in ecosystems: proceedings of the NATO advanced research workshop on the comparative roles of suspension-feeders in ecosystems Nida, Lithuania. 4–9 October 2003

NFRDI (2012) Standard manual of pacific oyster hanging culture. National fisheries research and development institute, Busan, p 38

Oh K, Pang I, Hofmann EE, Kim Y, Kim S, Park Y, Choi K (2002) Modeling oyster populations dynamics -I effect of available food on growth of the Pacific oyster *Crassostrea gigas* in Goseong Bay Korea. J Korean Fish Soc 35(4):327–335

Park BH, Park MS, Kim BY, Hur SB, Kim SJ (1988) Culture of the Pacific oyster (*Crassostrea gigas*) in the Republic of Korea. https://www.fao.org/3/ab706e/AB706E00.htm. Accessed 11 Dec 2023

Park YC, Kim PH, Jung YJ, Lee KJ, Kim MS, Go KR, Park SG, Kwon SJ, Yang JH, Mok JS (2016) Seasonal variation of physicochemical factor and fecal pollution in the Hansan-Geojeman area, Korea. Fish Aquat Sci 19(1):1–9. https://doi.org/10.1186/s41240-016-0017-9

Park M, Shin SK, Do YH, Yarish C, Kim JK (2018) Application of open water integrated multi-trophic aquaculture to intensive monoculture: a review of the current status and challenges in Korea. Aquaculture 497:174–183. https://doi.org/10.1016/j.aquaculture.2018.07.051

Peterson CH, Grabowski JH, Powers SP (2003) Estimated enhancement of fish production resulting from restoring oyster reef habitat. Mar Ecol-Prog Ser 264:249–264. https://doi.org/10.3354/meps264249

Piazza BP, Banks PD, La Peyre MK (2005) The potential for created oyster shell reefs as a sustainable shoreline protection strategy in Louisiana. Restor Ecol 13(3):499–506. https://doi.org/10.1111/j.1526-100X.2005.00062

Reid GK, Chopin T, Robinson SMC, Azevedo P, Quinton M, Belyea E (2013) Weight ratios of the kelps, *Alaria esculenta* and *Saccharina latissima*, required to sequester dissolved inorganic nutrients and supply oxygen for Atlantic salmon, *Salmo salar*, in integrated multi-trophic aquaculture systems. Aquaculture 408–409:34–46. https://doi.org/10.1016/j.aquaculture.2013.05.004

Ren JS, Marsden ID, Ross AH, Schiel DR (2003) Seasonal variation in the reproductive activity and biochemical composition of the Pacific oyster (*Crassostrea gigas*) from the Marlborough Sounds, New Zealand. NZJ Mar Freshw Res 37(1):171–182. https://doi.org/10.1080/00288330.2003.951715

Schatte Olivier A, Jones L, Vay LL, Christie M, Wilson J, Malham SK (2018) A global review of the ecosystem services provided by bivalve aquaculture. Rev Aquacult 12(1):3–25. https://doi.org/10.1111/raq.12301

Shatkin G, Shumway SE, Hawes R (1997) Considerations regarding the possible introduction of the Pacific oyster (*Crassostrea gigas*) to the Gulf of Maine: a review of global experience. J Shellfish Res 16:463–478

Shim J, Lee SJ, Jeong RH (2021) Long-term change and factors affecting the fatness of the pacific oyster *Crassostrea gigas* in tongyeong-geoje bays, Korea. Korean J Fish Aquat Sci 54(4):434–444. https://doi.org/10.5657/KFAS.2021.0434

Sidwell V, Bonnet J, Zook E (1973) Chemical and nutritive values of several fresh and canned finfish, crustaceans, and mollusks. Part 1: proximate composition, calcium and phosphorus. Mar Fish Rev 35(12):16–19

Zhou Y, Yang H, Liu S, He Y, Zhang F (2002) Chemical composition and net organic production of cultivated and fouling organisms in Sishili Bay and their ecological effects. J Fish China 26(1):21–27