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Simple Indicators for Assessing Sustainability of Marine Aquaculture in Miyagi, Mie, and Kagoshima Prefectures, Japan

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ABSTRACT

The assessment of aquaculture sustainability is a vital process that focuses on optimizing aquaculture production while mitigating environmental impacts, notably eutrophication. In this study, straightforward indicators were employed to assess the sustainability of coho salmon, red seabream, yellowtail, and bluefin tuna aquaculture in both enclosed bays and open water areas of Miyagi, Mie, and Kagoshima prefectures. This assessment was based on annual aquaculture production estimates, nutrient load, and farms' locations. The sustainability indicators, $\Sigma I2$ and $\Sigma I3$, exhibited significant variations among marine aquaculture setups in different enclosed bays. These indicators were further validated through the occurrences of red tides and the extent of bay closure. Higher values of sustainability indicators ($\Sigma I2$ and $\Sigma I3$) in enclosed bays correlated with more substantial aquatic environmental consequences, indicating lower marine aquaculture sustainability. The study highlighted a direct relationship between nutrient load and the distance of aquaculture farms from the bay mouth, showcasing the higher impacts of marine aquaculture on the aquatic environment in closer proximity. Bluefin tuna farming, known for its high feed conversion ratio and significant environmental impact, exhibited a higher nutrient load per unit production weight compared to other fish species. Coho salmon demonstrated a lower nutrient load per production, while red seabream and yellowtail exhibited relatively similar values. Interestingly, bluefin tuna's nutrient load per economic yield was relatively low due to the fish's high market price. These research findings provide valuable insights for aquaculture administrators, enabling them to estimate annual fish production and associated nutrient loads in marine aquaculture. This information is crucial for implementing an ecosystem approach, ensuring the long-term sustainability of marine aquaculture practices.

INTRODUCTION

Aquaculture, indeed, is a promising alternative to fisheries, and it has grown while wild fish stocks have decreased **(Troell *et al.*, 2014; Naylor *et al.*, 2021)**. Increased production from marine aquaculture has contributed to bringing previously high-priced species within reach of the average consumer **(De Silva, 2001)**. Additionally, it has an enormous potential to meet global seafood demand **(Costello *et al.*, 2020)**. The expansion of aquaculture raises a number of issues directly related to its sustainable development **(Lazard *et al.*, 2011)**. For example, in intensive marine finfish aquaculture, sediments and nutrients generated in excess are introduced into the marine aquatic environment **(Alleway *et al*., 2019; Rosa *et al.*, 2020)**. This influx is potentially linked to environmental degradation, notably causing the occurence of some phenomena such as eutrophication in aquatic ecosystems **(Howarth *et al*., 2011)**. The majority of aquaculture farms are situated in enclosed bay areas along the coast of Japan, where the seawater exchange rate is relatively low. This situation often leads to frequent occurrences of eutrophication. In enclosed bays, the cross-sectional area of the bay mouth is small compared to the maximum cross-sectional area of the bay. This limited opening restricts seawater exchange, making these areas susceptible to water pollution and eutrophication. Notably, Japan has designated 88 such enclosed bay areas. Despite such problems, enclosed bay areas are blessed with a calm natural environment and have been used as fishing grounds for a long time **(International EMECS Center, n.d.)**. Microflora of an aquatic ecosystem can be impacted by an accumulation of organic enrichment of sediments underlying fish farms through discharges and waste products **(Holmer *et al*., 2005)**. Eutrophication affects the overlying water column in aquatic environments, leading to significant changes in sediment chemistry **(Terlizzi *et al*., 2010)**. Furthermore, marine aquaculture-based seafood production might be disrupted as a consequence **(Fitridge *et al*., 2012)**.

Estimating the annual aquaculture production from identified farms is crucial for calculating aquaculture intensity. With the growth of marine aquaculture production, an increase in intensity is anticipated **(Oddsson, 2020)**. Nutrient load that are associated with the productions of aquaculture are calculated by residual feeds and wastes from aquaculture **(Bueno *et al*, 2017; Gao *et al*., 2022)**. The ability to exchange nutrients from the bay to the open ocean depends on the width of the bay mouth and the distance from farms to the bay mouth **(Yokoyama, 2010)**. Nutrient load generated eutrophication such as red tides that severely affected marine aquaculture production in enclosed bays **(International EMECS Center, n.d.)**.

The ratio of nutrient load to the farm volume is an important indicator of the environmental impact of aquaculture farms. The identification of aquaculture cages in a fish farm from satellite images using object detection can be achieved through the application of deep learning techniques **(Ren *et al*., 2015, Gao *et al*., 2019)**. The rapid adoption of deep learning technology in a variety of fields including aquaculture has created both new opportunities and challenges for information and data processing **(Zhao *et al*., 2021)**.

Sustainability assessment of marine aquaculture is crucial, with a focus on factors such as annual production, nutrient load estimation, and the location of aquaculture farms. These factors can significantly impact the environmental capacity of the aquaculture area **(Gao *et al*., 2022)**. We employed simple indicators to assess the sustainability of marine aquaculture, primarily focusing on majorly produced finfish species. These included coho salmon in Miyagi prefecture, red seabream, and bluefin tuna in Mie prefecture in addition to yellowtail and bluefin tuna aquaculture in Kagoshima prefecture. The outcomes of the sustainability indictors' analysis were further verified with red tides occurrences and the degree of closure of the enclosed bay. We observed the effect of aquatic environmental issues on marine finfish aquaculture to promote sustainable development of marine aquaculture in different enclosed bays in Japan.

MATERIALS AND METHODS

1. Study areas

Marine aquaculture stands as a vital food-producing industry in Japan. According to the Ministry of Agriculture, Forestry and Fisheries (MAFF) of Japan, it contributed to approximately 249,491 tons (25%) of the overall marine aquaculture production in fiscal year (FY) 2018 and 248,137 tons (27%) in FY 2019 **(MAFF, 2021)**. The aquaculture industry includes marine finfish species that are predominantly produced in Japan, including coho salmon (*Oncorhynchus kisutch*), red seabream (*Pagrus major*), yellowtail (*Seriola quinqueradiata*, *S. dumerili*, and *S. lalandi*), and bluefin tuna (*Thunnus orientalis*) **(Abo *et al*., 2013; Matsuura *et al*., 2019; Watanabe & Sakami, 2021)**.

The aquaculture farms selected for sustainability assessment in the study areas were based on the majority of aquaculture species and their production. These farms include coho salmon in Miyagi prefecture, red seabream and bluefin tuna in Mie prefecture, as well as yellowtail and bluefin Tuna in Kagoshima prefecture. Marine aquaculture of coho salmon in Miyagi contributed approximately to 88% of total coho salmon production in Japan **(MAFF, 2021)**. Both red seabream and bluefin tuna of Mie contributed on an average of 6%, whereas from Kagoshima, yellowtail and bluefin tuna contributed on an average 32% and 17% of total production during FY 2018 to FY 2019, respectively **(MAFF, 2021)**. In Miyagi prefecture, there are 3 enclosed bays, while Mie has 5, and Kagoshima has 4. These bays house various aquaculture farms producing different species (Fig. 1). Along with the farms in enclosed bays, several marine aquaculture farms are also identified outside of the studied 12 enclosed bays and are considered as open water areas (Fig. 1). Colored triangles denote the fish farms with multiple cages where single to multi-species aquaculture exist. Enclosed bays and their areas are listed in the **International EMECS Center, n.d.**

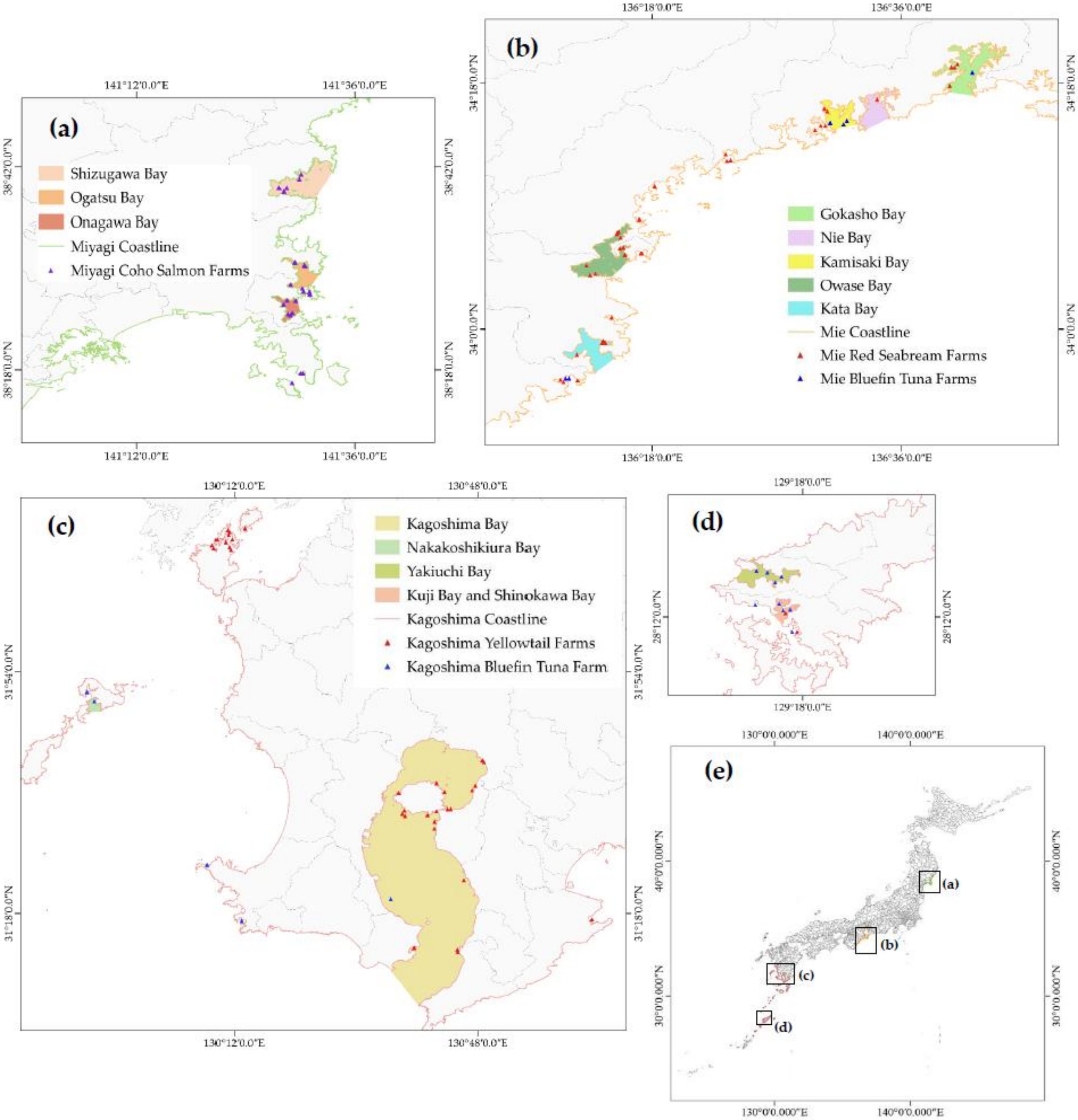

Fig. 1. Maps showing 111 marine aquaculture farms and 12 enclosed bays in (a) Miyagi, (b) Mie, (c) Kagoshima prefectures, (d) Amami Island of Kagoshima in Japan, and (e) Entire Japan. Colored triangles indicate aquaculture farms, and colored filled areas indicate enclosed bays analyzed.

2. Aquaculture farms, annual fish production and nutrient load estimation

2.1. Aquaculture cage detection and area calculation

Aquaculture farms locations and areas are obtained from the MDA Situational Indication Linkages and the Aquaculture Ground Database. Aquaculture Ground

Database includes a map of aquaculture fishing grounds focusing on the coho salmon, red seabream, bluefin tuna and yellowtail. Mean depth of aquaculture farms was estimated from the new pec smart (an application program made by mapple-on). The area and number of the aquaculture cages were identified and calculated manually based on historical satellite images of the aquaculture farms during FY 2018 to FY 2019 from Google Earth Pro software. However, some farms were also analyzed by object detection in Tensorflow Faster Region based Convolutional Neural Networks (TF Faster R-CNN), where the aquaculture cage was displayed in a bounding box with level of confidence.

2.2. Estimation of annual fish production

The annual fish production is calculated as the total farm production divided by the number of years between stocking and final harvesting, as defined by **Gao *et al.* (2019)**. The estimated annual fish production for each farm was calculated using the formula derived from **Gao *et al.* (2022)**, which is as follows:

$$p = \sum_{s=1}^{m} \left(\frac{P_s}{T_s}\right) \qquad (1)$$

Where, p (kg/year) is the estimated annual fish production of each farm. Variable m is the number of species reared in a farm, and s indicates fish species; P_s (kg) is the estimated total production of each farm in T_s (year) of species s; T_s is the period between stocking and harvesting of species s, and P_s is estimated using the method implemented by **Gao *et al.* (2022)**, as follows:

$$P_s = R_s \times \sum_{i=1}^{n} \rho V_i, \qquad (2)$$

where n is the number of aquaculture cages in each farm; V_i (m^3) is the volume of fish cage i; $V = (a \times d)$; a = cage area (m^2); d = cage mean depth (m); ρ (1025 kg/m^3) is the density of seawater; R_s is the "species stock rate" of species s, which means weight ratio of stocked fish and seawater inside the cage when the fish are available for final harvest, and n denotes the number of cages used for species s in a farm **(Gao *et al.*, 2022)**.

The statistical production for each farm in each year is not disclosed, while the prefecture-wide production $\Sigma_s P_s$ by year by fish species is disclosed. From Equation 2, we assume that each cage production is in proportion to its volume. For multi-species, aquaculture and the fish species that take two years or more to final harvest, the number of cages in farms used for final harvest in a particular year is unknown, but we assume that the same volume of cages in farms is produced each year. From Equation 2, $\Sigma_{\text{pref}} P_s = R_s(\Sigma_{\text{pref}}\, \rho V)/T_s$, so $R_s = \Sigma_{\text{pref}}\, P_s T_s\, /(\Sigma_{\text{pref}}\, \rho V)$, where the sum "$\Sigma_{\text{pref}}$" is taken for the entire prefecture. The production P_s for each farm is calculated using Equation 2 with R_s. The production per year of farm is given by $p = \Sigma_{\text{farm}} P_s/T_s = (\Sigma_{\text{farm}} \rho V)\Sigma_{\text{pref}} P_s/(\Sigma_{\text{pref}}\, \rho V)$, in which T_s is cancelled. Average depth of each aquaculture cage is assumed as shown in Table (1), by interviewing some prefectural fish farmers. The statistical production ΣP_s for each fish species in each prefecture is known. We estimated the total volume ΣV_i of all farms by $\Sigma(a \times d)$. The mean value of R_s can be estimated by using $\Sigma P_s/\Sigma \rho V_s$.

However, the stock rate is subjected to change due to the natural mortality of fish caused by typhoon and other natural disasters.

Table 1. Aquaculture period, mean depth of cages and statistical marine aquaculture production in FY 2018 and FY 2019

Prefecture	Aquaculture species	Culture period (years)	Cages mean depth (m)	Estimated stock rate (%)		Statistical production (ΣP_s, tons)	
				2018	2019	2018	2019
Miyagi	Coho salmon	1	10	2.25	2.01	15867	14179
Mie	Red seabream	2	8	0.27	0.26	3824	3809
	Bluefin tuna	3	10	0.09	0.13	950	1390
Kagoshima	Yellowtail	2	8	1.40	1.30	46277	43039
	Bluefin tuna	3	10	0.16	0.17	3083	3362

2.3. Estimation of annual nutrient load

The nutrient component ratios released from aquaculture farms depend on the content of nitrogen and phosphorus in the feed. Although these ratios vary among fish species and aquaculture sites, on average they are close to the Redfield ratios; T_C (total carbon): T_N (total nitrogen): T_P (total phosphorus) = 1: 0.2: 0.03 **(Gao *et al*., 2022)**.

The dry weight of carbon (DW_C) from aquaculture farms was estimated from feed conversion ratio (FCR), water content of feed (WC_F) and water content of fish (WC_f), which depends on species **(Gao *et al*., 2022)**,

$$DW_C = WW_f \times [FCR \times (1 - WC_F) - (1 - WC_f)] \times CC, \tag{3}$$

where CC is the carbon content (40%) in the discharged wastes from aquaculture farms. The first term in the Equation 3, $WW_f \times FCR \times (1 - WC_F) \times CC$, is the dry weight of carbon of the feed and the second term $WW_f \times (1 - WC_f) \times CC$, is the dry weight of carbon of the fish. Therefore,

$$T_C = p \times [FCR \times (1 - WC_F) - (1 - WC_f)] \times CC, \tag{4}$$

where p is the annual production of the aquaculture farm. We use WC_F, and WC_f for red seabream, and yellowtail as given by **Gao *et al*. (2022)**. Since compound feed is used for coho salmon aquaculture, WC_F and WC_f of coho salmon are similar with red seabream and yellowtail. WC_f for bluefin tuna is 75% and WC_F is 60% as we assumed bluefin tuna required feed composed of both raw fish and fish meal in their diet from expert opinion (I Nagano, pers. comm.). We considered FCR for coho salmon, red seabream, and yellowtail from **JFA (2014)**. While, the opinion of expecrts regarding bluefin tuna was considered from the study of **Ono and Nakahara (2009),** as shown in Table (2). T_N and T_P are calculated from T_C according to the Redfield ratio: *e.g.*, $T_N = 0.2\ T_C$. These fish species also differ in fish price (denoted by q). The economic yield per production y is expressed by qp. In addition to the nutrient load per production, Table (2) also presents the nutrient load per economic yield. The fish price for each species was sourced from Minato Shimbun and utilized in our calculations.

Table 2. Parameters for calculating nutrient load in marine aquaculture farm

Parameter	**Aquaculture species**			
	Coho salmon	**Red seabream**	**Yellowtail**	**Bluefin tuna**
FCR	1.3–$\underline{1.5}$	2.5–$\underline{2.7}$	2.3–$\underline{2.8}$	13–$\underline{15}$
WC_F (%)	10	10	10	60
WC_f (%)	75	75	75	75
T_N/p	0.07–0.09	0.16–0.17	0.15–0.18	0.40–0.46
Price *q* (JPY/kg)	500	600	1000	2500
T_N/y (kg/1000JPY)	0.15–0.18	0.27–0.29	0.15–0.18	0.16–0.18

From the above Equation, a relationship between production weight (*p*) and nitrogen load (T_N) can be derived. It is evident that the nutrient load of bluefin tuna is higher, whereas that of coho salmon is lower, primarily attributed to the feed conversion ratio (*FCR*). However, as bluefin tuna has a higher fish price, the nitrogen load per economic yield (*y*) of bluefin tuna is considered to be low. Therefore, comparisons are made not only for production weight *p*, but also for production price *y*. Values for *FCR* and nutrient load are given as intervals in Table (2), but the underlined values will be used in subsequent calculations.

3. Calculation of sustainability indicators

We conducted the present study to understand the practicability of the sustainability indicators in marine aquaculture on the basis of different parameters. Based on the annual fish production from each aquaculture farm, the sustainability of aquaculture can be evaluated through the following indicator, I_1 as taken from **Gao *et al.* (2020)**. Aquaculture production per farm, also referred to as the aquaculture intensity index by **Gao *et al.* (2019)**, has been a long-standing metric used to assess the production capacity of a site **(Oddsson, 2020)**.

$$I_1 = \frac{p}{A \times H} = \frac{R_S \times \rho \times (a \times d)}{T_S \times A \times H} \qquad (5)$$

Where, *p* (kg) is farm's annual fish production derived from the Equation 1; *A* (m^2) is surface area, and *H* (m) is mean depth of the farm site.

To consider the environmental impact, the nitrogen load per farm (kg/year) can be an important indicator. This is based on total nitrogen (T_N) instead of *p* in I_1. We defined the nitrogen load per farm, I_2, as:

$$I_2 = \frac{T_N}{A \times H}. \qquad (6)$$

However, the distance of the aquaculture farm from the bay mouth, denoted by D (m), is significant for exchanging nutrient load. To this end, **Gao *et al*. (2022)** defined the following indicator:

$$I_3 = \frac{T_N \times D}{A \times H}. \qquad (7)$$

Gao *et al*. (2022) calculated indicator I_4 using T_P instead of T_N in I_3 and compared them with the nutrient loads from land inflow. Given the assumption of the Redfield ratio, the ration of I_3 and I_4 for each farm precisely corresponds to the Redfield ratio of T_N and T_P. Hence, I_4 is not utilized in the calculation for the phosphorus load.

Compared to I_1, the higher the FCR, the lower the water content WC_F of the aquaculture species and the longer the distance (D) from the bay mouth, the higher the value of I_3 and the higher the environmental impact.

4. Red tides, the degree of closure and correlation analysis of the indictors

Duration of red tides information in the enclosed bays of studied prefectures during FY 2018 and FY 2019 were collected from the website of the prefectural government (Table A.1). Regulations of wastewater in enclosed bays depend on the degree of closure, which is defined as:

$$C = \frac{\sqrt{S} \times D_1}{W \times D_2}$$

Where, S and W are the area of enclosed bay and the width of bay mouth, respectively, and D_1 and D_2 are the maximum water depth in the bay and the maximum water depth along the bay mouth **(International EMECS Center, n.d.)** (Table A.2).

Once we found I_1, I_2, and I_3 of each aquaculture in an enclosed bay, we calculated ΣI_1, ΣI_2, and ΣI_3 of all the studied aquaculture in each enclosed bay during FY 2018 and FY 2019. The total number of aquaculture farms varied among the enclosed bays. Therefore, cumulative values for the sustainability indicator, ΣI_1, ΣI_2, and ΣI_3 in each enclosed bay are also considered. Moreover, we calculated the correlation coefficient for each enclosed bay's ΣI_1, ΣI_2, and ΣI_3 with red tides occurrences in each enclosed bay during FY 2018 and FY 2019 and the degree of closure (C) to evaluate the validity of the indicators for aquaculture sustainability assessment.

RESULTS

1. Aquaculture cage detection and area calculation

Aquaculture farms among the three prefectures varied in numbers and areas. Total 5918 aquaculture cages of 943272m^2 area were identified (Table 3). Shape of aquaculture cages varied depending on the species cultured. Coho salmon is primarily cultured in octagonal-shaped cages, whereas red seabream and yellowtail are raised in square cages, and bluefin tuna is cultivated in circular and rectangular-shaped cages.

Table 3. Estimation of aquaculture area and cages information identified from the satellite images analysis

Prefecture	**Aquaculture species**	**Farms number**	**Total farms area (ha)**	**Total cages number**	**Total cages area (m^2)**
Miyagi	Coho Salmon	22	121	292	68701
Mie	Red Seabream	35	246	1632	175645
	Bluefin Tuna	6	64	48	102460
Kagoshima	Yellowtail	34	1786	3833	404210
	Bluefin Tuna	14	184	113	192256

2. Estimation of annual aquaculture production

We obtained the total production (P_s) of each farm using the R_s for the entire prefecture using equation (2). In addition, using equation (1), we estimated the annual production (*p/year*). The estimated aquaculture productions of coho salmon, red seabream, bluefin tuna and yellowtail from the farms of the 12 enclosed bays accounted for more than half of the aquaculture production in Miyagi, Mie and Kagoshima prefectures (Fig. 2). A total of 15 out of 22 coho salmon aquaculture farms are situated in enclosed bay areas in Miyagi. In Mie, there are 20 out of 35 red seabream farms, and 4 out of 6, bluefin tuna farms are located in enclosed bays. Additionally, in Kagoshima prefecture, there are 21 out of 34 yellowtail farms, and 9 out of 14 bluefin tuna farms located in enclosed bay areas. In FY 2018, the estimated coho salmon aquaculture production from enclosed bays in Miyagi was 9004 tons, and 8046 tons in FY 2019, which contributed to around 57% of estimated annual coho salmon production in Miyagi (Fig. 2). Estimated annual production from red seabream in combination with bluefin tuna from enclosed bays in Mie was 1635 tons and 1725 tons in FY 2018 and FY 2019, respectively, which shared around 73% of estimated annual production. In Kagoshima, the annual production form yellowtail in combination with bluefin tuna from enclosed bays was 13753 tons in FY 2018 and 12900 tons in FY 2019, which shared around 57% of estimated annual production in Kagoshima, respectively (Fig. 2).

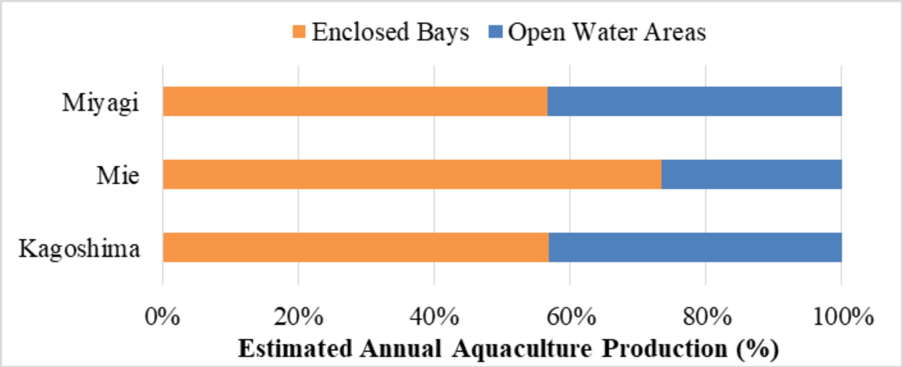

Fig. 2. Estimated annual aquaculture production (%) from enclosed bays and open water areas in Miyagi, Mie, and Kagoshima prefectures in FY 2018

3. Estimation of annual nutrient load

Nutrient load estimated from aquaculture productions of coho salmon, red seabream, bluefin tuna and yellowtail are varied among 3 prefectures during FY 2018 and FY 2019 (Table 4). Feed conversion ratio (*FCR*) of different aquaculture species have great significance for the estimation of nutrient load. Production of nutrient load depend on the number of cages and annual production from each cage. In FY 2018, estimated annual total nitrogen (T_N) from coho salmon aquaculture farms in enclosed bays in Miyagi prefecture was 792 tons, whereas it was 708 tons in FY 2019 (Table 4). Around 57% of the annual nutrient load produced from different enclosed bays' coho salmon farms is in Miyagi (Fig. 3). In Mie prefecture, estimated annual T_N from red seabream was 249 tons in FY 2018 and 248 tons in FY 2019, and from bluefin tuna, it was 95 tons and 139 tons in FY 2018 and FY 2019, respectively (Table 4). Annual nutrient load from red seabream and bluefin tuna in enclosed bays shared around 75% and 65% , respectively, in Mie (Fig. 3). Estimated annual T_N from the enclosed bays in Kagoshima prefecture from yellowtail aquaculture was 2374 tons in FY 2018 and 2208 tons in FY 2019, while from bluefin tuna, it was 312 and 340 tons in FY 2018 and FY 2019, respectively (Table 4). Enclosed bays in Kagoshima prefectures shared around 57% of yellowtail and 66% of bluefin tuna estimated nutrient load (Fig. 3).

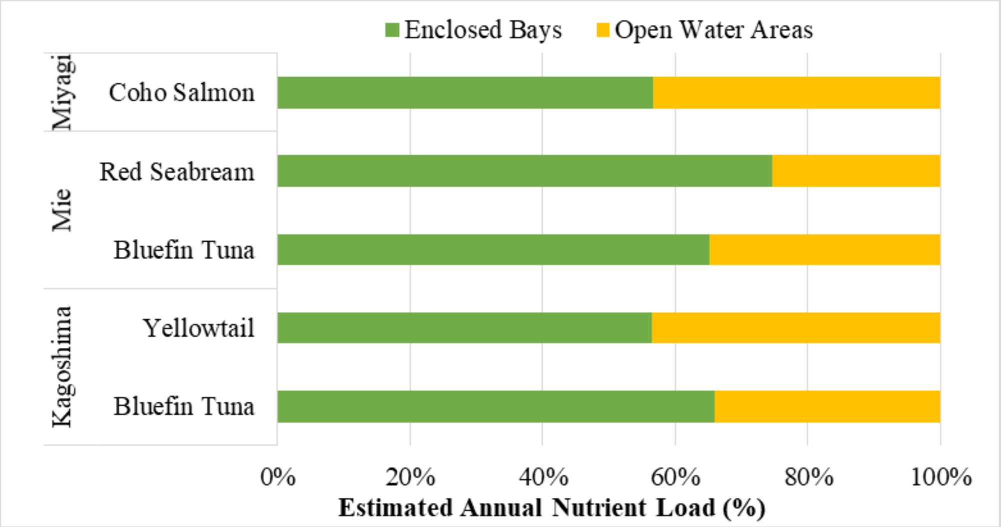

Fig. 3. Estimated annual nutrient load (%) from enclosed bays and open water areas in Miyagi, Mie and Kagoshima prefectures in FY 2018

Table 4. Estimated nutrient load in the 12 enclosed bays and open water areas during FY 2018 and FY 2019

Prefecture	Areas	Farm IDs**	Aquaculture species*	Total nitrogen (tons/year)	
				FY 2018	FY 2019
Miyagi	**Enclosed Bays**				
	Shizugawa	1-5	C	399	356
	Ogatsu	6-9	C	164	147
	Onagawa	10-15	C	230	205
	Open Water				
	Izushima	16-19	C	356	318
	Ayukawa	20-21	C	183	163
	Ajishima	22	C	65	58
Mie	**Enclosed Bays**				
	Gokasho	1-5	S, T	63	74
	Nie	6	S	16	16
	Kamisaki	7-11	S, T	79	112
	Owase	12-20	S	158	157
	Kata	21-24	S	28	28
	Open Water				
	Minamiise	25-27	S	18	18
	Taiki	28-30	S	18	18
	Kihoku	31-33	S	15	15
	Sugari	34-35	S	12	12
	Kuki	36	S	2	2
	Kumano	37-41	S, T	70	94
Kagoshima	**Enclosed Bays**				
	Kagoshima	1-21	Y, T	2335	2173
	Nakakoshikiura	22	T	4	4
	Yakiuchi	23-26	T	181	198
	Kuji and Shinokawa	27-30	Y, T	166	173
	Open Water				
	Kimotsuki	31	Y	105	98
	Minami Satsuma	32-33	T	23	25
	Kuwanoura	34	T	64	70
	Nagashima	35-45	Y	1560	1451
	Setouchi	46-48	Y, T	236	232

*C= Coho Salmon, S= Red Seabream, T= Bluefin Tuna, and Y= Yellowtail.

** Farm IDs indicate sequential number of the farms in enclosed bays and open water areas, respectively.

4. Calculation of sustainability indicators

4.1. I_1 and I_2 index of all aquaculture farms

We calculated I_1 and I_2 values for the aquaculture farms located in both enclosed bays and open water areas. Since the nutrient load was estimated from aquaculture fish production using the Redfield ratio, I_2 tended to be similar to I_1 in enclosed bays and open water areas in the studied prefectures. The I_1 values among 22 coho salmon aquaculture farms in Miyagi prefecture varied significantly. I_1 values ranged from 0.12 to 4.06 in FY 2018 and 0.10 to 3.63 in FY 2019 in Miyagi (Fig. 4a). In Mie prefecture, 35 red seabream farms, and 6 bluefin tuna aquaculture farms were identified. The I_1 values of red seabream farms in Mie ranged from 0.01 to 0.16 in both FY 2018 and FY 2019, whereas in bluefin tuna farms, I_1 values ranged from 0.01 to 0.04 and 0.01 to 0.05 in FY 2018 and FY 2019, respectively (Fig. 4b). In total, 34 yellowtail farms were identified in Kagoshima prefecture, and I_1 values ranged from 0.003 to 0.73 in FY 2018, whereas in FY 2019, I_1 values of yellowtail farms ranged from 0.003 to 0.68 (Fig. 4c). Among 14 identified bluefin tuna farms in Kagoshima, I_1 values ranged from 0.003 to 0.04 in both FY 2018 and FY 2019.

I_2 values ranged from 0.01 to 0.36 in FY 2018; whereas, values fluctuated from 0.01 to 0.32 in FY 2019 for coho salmon aquaculture in Miyagi (Fig. 4d). The deviation in I_2 from FY 2018 to FY 2019 were 0.1% to 3.8% among 22 coho salmon aquaculture farms. For red seabream aquaculture, we found I_2 values of 0.002 to 0.03 in both FY 2018 and FY 2019, whereas for bluefin tuna farms, values recorded ranged from 0.003 to 0.02 in FY 2018 and from 0.04 to 0.02 in FY 2019 in Mie (Fig. 4e). The deviation of I_2 between FY 2018 and FY 2019 ranged from 0– 0.01% in red seabream farms and 0.1– 0.8% in bluefin tuna farms in Mie. In Kagoshima, I_2 values ranged from 0.001 to 0.13 in FY 2018 and from 0.0005 to 0.12 in FY 2019 for yellowtail farms, whereas for bluefin tuna farms, values fluctuated from 0.001 to 0.02 in FY 2018 and 0.002 to 0.02 in FY 2019 (Fig. 4f). Deviation of I_2 in Yellowtail aquaculture ranged from 0–0.9%, whereas a range of 0.01–0.2% was recorded for bluefin tuna from FY 2018 to FY 2019 in Kagoshima. The phenomenon indicated that, I_2 values of the marine aquaculture vary considerably in terms of annual nutrient load production.

Variations in I_1 and I_2 values between years were small for all farms. This suggests that I_1 values and annual production, I_2 values and annual nutrient load varied between farms rather than between years. The area and mean depth of each farm were the same in both years, suggesting that the variation in annual production is reflected in the variation in I_1, and variation in annual nutrient load is reflected in the variation in $I_{2.}$ The I_1 and I_2 values were slightly higher in FY 2018 for coho salmon in Miyagi and yellowtail in Kagoshima. However, they were slightly higher in FY 2019 for bluefin tuna in Mie. There was little difference between red seabream in Mie and bluefin tuna in Kagoshima prefecture. For coho salmon, I_1 and I_2 values tended to be higher in open water farms than in enclosed bay farms. In Mie Prefecture, I_1 and I_2 values tended to be higher in red seabream farms in enclosed bays. In Kagoshima prefecture, disparities by region and farm were observed, such as higher I_1 and I_2 for yellowtail farms in Nagashima and lower I_1 and I_2 for one bluefin tuna farm in Kagoshima Bay.

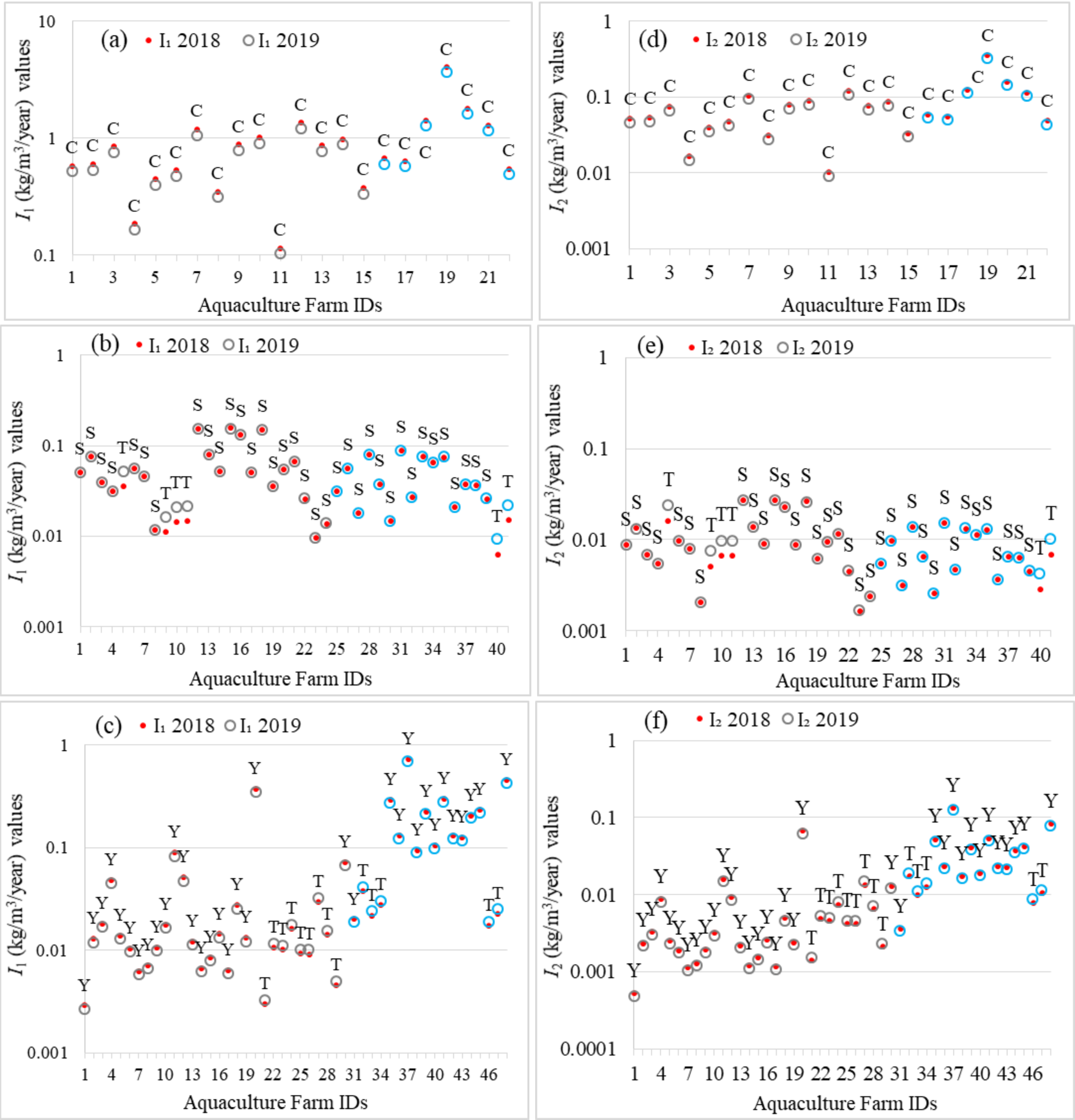

Fig. 4. Graphs showing I_1 (a–c) and I_2 (d–f) values of different (a, d) Coho salmon (labeled "C") farms in Miyagi prefecture, (b, e) Red seabream ("S") and Bluefin tuna farms ("T") in Mie prefecture, (c, f) Yellowtail ("Y") and Bluefin tuna farms in Kagoshima prefecture. Red dots, and open circles indicate I_2 in FY 2018, and FY 2019, respectively. Grey and Blue circles indicate aquaculture farms in enclosed bays, and open water, respectively. Numbers in horizontal axis indicate farm IDs, as shown in Table (4)

4.2. Comparison between I_1, I_2 and I_3 indices in enclosed bays

The values of I_1, I_2 and I_3 were compared for aquaculture farms in enclosed bays (Fig. 5). Coho salmon had lower I_3 for higher I_1, mainly because farms for coho salmon are located at the shorter distance (*D)* from the bay mouth. Farms for bluefin tuna also have shorter *D*, but due to their high *FCR*, they have a high nutrient load per production. Around 62% (69) of the total 111 studied aquaculture farms are located in enclosed bay areas in the 3 prefectures. Therefore, distance from the aquaculture farms to bay mouth is an important factor along with the nutrient load for aquaculture sustainability.

Nutrient load, i.e., total nitrogen (T_N) estimated from different aquaculture farms are associated with distance from the aquaculture farms to bay mouth. I_3 values varied significantly among the aquaculture farms in the studied enclosed bays. In enclosed bays, I_3 values ranged from 5 to 387 in FY 2018, whereas values fluctuated from 4 to 346 in FY 2019 for coho salmon farms in Miyagi (Fig. 5). In the enclosed bay areas in Mie, I_3 values ranged from 1 to 138 in FY 2018 and from 1 to 137 in FY 2019 for red seabream farms, whereas values ranged from 4 to 47 in FY 2018 and from 6 to 69 in FY 2019 for bluefin tuna farms (Fig. 5). For yellowtail aquaculture, I_3 values ranged from 23 to 1095 in FY 2018, and 22 to 1019 in FY 2019, whereas a range from 5 to 46 was recorded in FY 2018, and from 6 to 50 in FY 2019 for bluefin tuna aquaculture in enclosed bays in Kagoshima (Fig. 5).

A comparison of the ΣI_2, and ΣI_3 of all the studied aquaculture farms in each bay showed variation among the bays in each year (Table 5). Higher ΣI_2 value was found in Onagawa Bay followed by Ogatsu Bay, whereas higher ΣI_3 value was found in Kagoshima Bay, followed by Shizugawa Bay in both FY 2018 and FY 2019. The values of ΣI_2, and ΣI_3 in enclosed bays were comparatively higher in FY 2018 than FY 2019 (Table 5).

Table 5. ΣI_1, ΣI_2, and ΣI_3 in the enclosed bays with the degree of closure (*C*) and duration of red tides occurrence

Enclosed Bay	**FY 2018**			**FY 2019**			**Red tides* (days)**		***C*****
	ΣI_1	ΣI_2	ΣI_3	ΣI_1	ΣI_2	ΣI_3	**FY 2018**	**FY 2019**	
Shizugawa	2.67	0.23	1089	2.39	0.21	973	0	0	1.04
Ogatsu	2.97	0.26	866	2.65	0.23	774	0	0	1.48
Onagawa	4.71	0.41	691	4.21	0.37	618	1	0	1.39
Gokasho	0.23	0.05	181	0.25	0.06	202	36	1	1.81
Nie	0.06	0.01	27	0.06	0.01	27	0	1	1.08
Kamisaki	0.10	0.03	44	0.12	0.04	51	0	0	1.17
Owase	0.87	0.15	450	0.86	0.15	449	22	11	1.70
Kata	0.12	0.02	66	0.12	0.02	66	0	0	1.26
Kagoshima	0.75	0.14	4510	0.70	0.13	4200	50	11	6.26
Nakakoshikiura	0.01	0.005	13	0.01	0.01	15	0	15	1.20
Yakiuchi	0.04	0.02	97	0.05	0.02	106	0	0	2.01
Kuji and Shinokawa	0.12	0.04	72	0.12	0.04	74	0	0	1.20

*Table A.1; **Table A.2

Duration of red tides was also higher in FY 2018 than FY 2019 in different enclosed bays. The degree of closure (*C*) values among all the studied bays were more than 1, and higher *C* value was found in Kagoshima Bay (6.26) followed by Yakiuchi Bay (2.01).

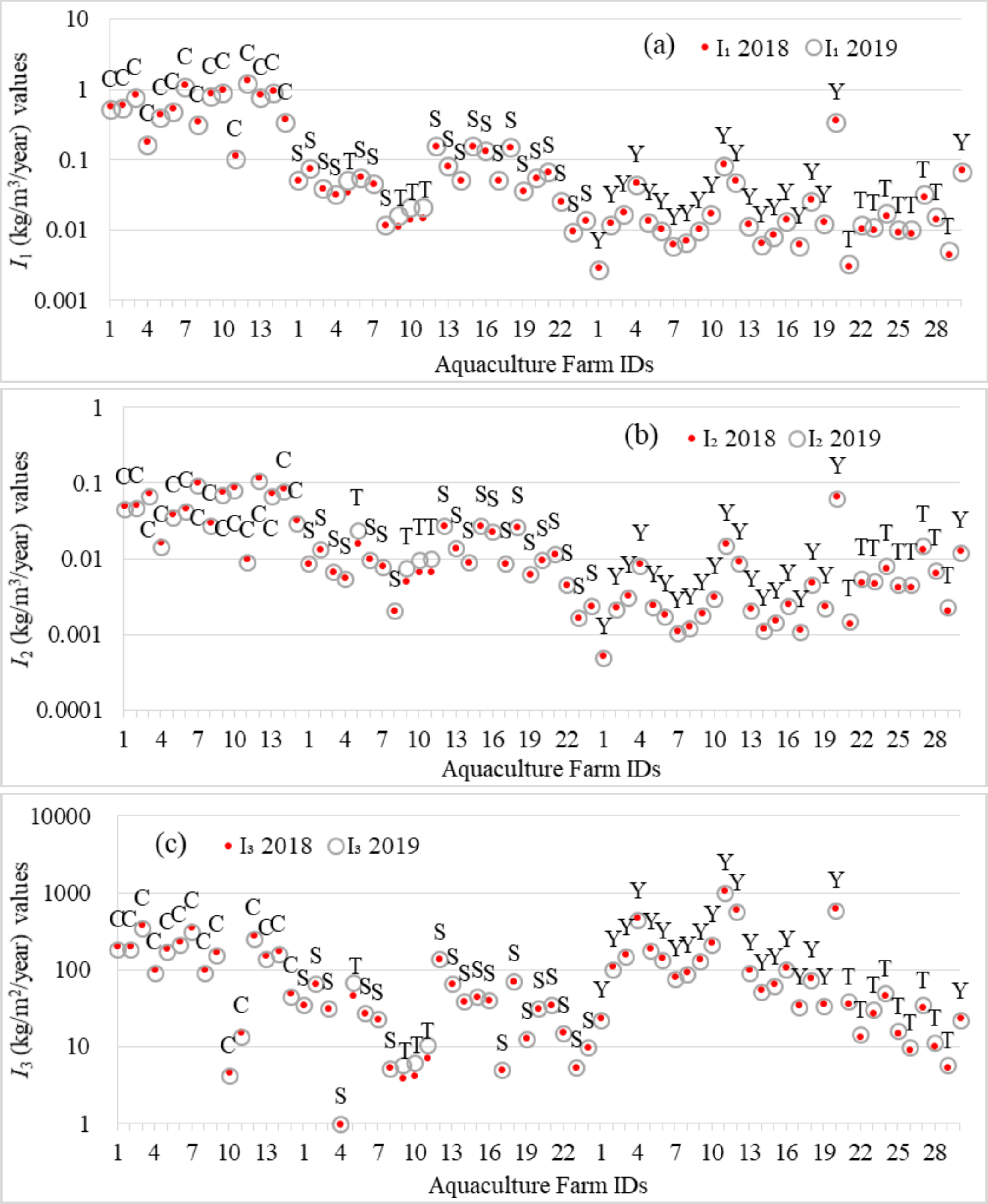

Fig. 5. Graphs showing (a) I_1, (b) I_2 and (c) I_3 values of aquaculture farms in enclosed bays. Red dots and open circles indicate values in FY 2018 and FY 2019, respectively. Labels "C", "S", "Y" and "T" indicate species, as shown in Fig. (4). Numbers in horizontal axis indicate farm IDs (from left to right: Miyagi, Mie, Kagoshima), as shown in Table (4).

5. Correlation of the indictors with red tides and the degree of closure

There were positive significant correlations among the ΣI_1, ΣI_2, and ΣI_3 for logarithmic scales in the aquaculture farms located in different enclosed bays (Table 6). Logarithms were employed due to the substantial variation, particularly in ΣI_3 values. Correlation coefficient (r) values found positive (0.541) between log ΣI_3 values in FY 2018 and red tides during FY 2018 (P=8.8%), and r (0.561) found between log ΣI_3 values in FY 2019 and red tides during FY 2018 (P=7.6%), whereas the red tide occurrence in FY 2019 is not significantly correlated with log ΣI_3 values in FY 2018 (P=92.6%) and log ΣI_3 values in FY 2019 (P=91.3%). We also discovered statistically significant correlations of log ΣI_3 in FY 2018 and FY 2019 with the degree of closure (C) (P=5.3% and 4.8%, respectively). These results remain qualitatively the same with the other *FCR* values, as shown in Table (2).

Table 6. Correlation among the ΣI_1, ΣI_2, and ΣI_3 in enclosed bays with the degree of closure (C) and red tides occurrences during FY 2018 and FY 2019, according to Table (5)

	Parameters	**FY 2018**			**FY 2019**			**FY 2018**	**FY 2019**
		log ΣI_1	log ΣI_2	log ΣI_3	log ΣI_1	log ΣI_2	log ΣI_3	Red tides	Red tides
FY 2018	log ΣI_2	0.983^{**}							
	log ΣI_3	0.864^{**}	0.895^{**}						
FY 2019	log ΣI_1	1^{**}	0.985^{**}	0.862^{**}					
	log ΣI_2	0.974^{**}	0.998^{**}	0.885^{**}	0.978^{**}				
	log ΣI_3	0.854^{**}	0.890^{**}	0.999^{**}	0.853^{**}	0.882^{**}			
FY 2018	Red tides	0.197	0.262	0.541	0.201	0.273	0.561		
FY 2019	Red tides	-0.231	-0.181	0.031	-0.235	-0.190	0.036	0.446	
	C	0.167	0.235	0.605	0.163	0.231	0.617^{*}	0.807^{**}	0.434

'*' and '**' denote significance levels of 5% and 1%, respectively.

DISCUSSION

1. Aquaculture production and nutrient load

Aquaculture production and nutrient load varied significantly among all farms of the coho salmon in Miyagi, red seabream, and bluefin tuna in Mie, yellowtail, and bluefin tuna in Kagoshima prefecture. Large farm areas and low stocking densities create less chances of environmental pollution. Since aquaculture production involves with the addition of solids and nutrients to the marine environment, these inputs can potentially lead to environmental degradation **(Gentry *et al*., 2016)**. The average water depths of aquaculture farms ranged from approximately 12 to 27m in Miyagi, 8 to 41m in Mie, and 8 to 156m in Kagoshima prefecture. Greater water depth reduces the buildup of organic material beneath fish aquaculture area. Alternatively, smaller water depth increases the impact on the flora and fauna of aquaculture area that causes major changes in sediment chemistry, and thus affecting the overlying water column **(Terlizzi *et al*., 2010)**. Aquaculture farms with species that are tolerable for highly intensive aquaculture are often subjected to high nutrient loads. Conversely, in farms with species vulnerable to highly intensive aquaculture, nutrient load is mitigated for stable production. Some farms of coho salmon and yellowtail are the former, and farms of bluefin tuna are the latter.

The distance from 15 aquaculture farms to the bay mouth ranged from approximately 52 to 6240m in Miyagi, whereas 131 to 5092m for 24 farms in Mie, and 1591 to 76266m for 30 farms in Kagoshima prefecture. Greater distances between aquaculture farms and the bay's mouth point toward a lower chance of nutrients spreading from the farms to the outside of the bay **(Gao *et al*., 2020)**, which might be the cause for the environmental contamination and also reduces the aquacultural productivity **(Olsen *et al*., 2008)**. Residual feed and metabolic waste from fish release nitrogen and phosphorus into the water of aquaculture farms, potentially creating a significant source of nutrients within coastal areas **(Carballeira Braña *et al*., 2021)**. Nitrogen and phosphorus are two important components of aquaculture wastes, both of which are regarded as potential water contaminants with significant environmental consequences **(Piedrahita, 2003; Dauda *et al*., 2019)**, which may result in toxic algal blooms by the proliferation of primary producers in aquatic environment **(Paerl *et al*., 2018; Wang *et al*., 2018)**. The nutrient load per unit production weight from bluefin tuna aquaculture is higher due to the elevated feed conversion ratio (FCR). However, the nutrient load per economic yield is lower because the price of bluefin tuna is correspondingly higher. Conversely, nutrient load per unit production weight is lower for coho salmon with lower *FCR*, while nutrient load per economic yield is higher for coho salmon with lower price.

A higher amount of nutrient load from Coho Salmon aquaculture was detected in Shizugawa Bay, while in Owase Bay, it was from red seabream aquaculture. In Kagoshima Bay, the elevated nutrient load was observed from yellowtail and bluefin tuna aquaculture during FY 2018 to FY 2019. When farms are located closer to the bay mouth, nutrient loads can circulate and exchange more efficiently from enclosed bays to the open sea, reducing the risk of bottom pollution. Hence, managing the aquaculture environment sustainably involves utilizing aquatic resources effectively **(Frankic & Hershner, 2003)**.

2. Red tides and the degree of closure

In enclosed bay areas, water contamination and eutrophication are more likely to occur due to inadequate seawater exchange because the cross-sectional area at the bay's mouth is smaller than the bay's maximum cross-sectional area **(International EMECS**

Center, n.d.). Therefore, the width of bay mouth is a significant feature for the viability of nutrient circulation produced from aquaculture farms. In the recent years, overcrowded fish farms and excessive feeding have led to environmental deterioration of coastal areas, thought to be a major cause of eutrophication, red tides and fish diseases **(Makino, 2017)**. During FY 2018 to FY 2019, red tides affected 6 of the 12 studied enclosed bays in Miyagi, Mie and Kagoshima prefectures, whereas duration of red tides was higher in Owase and Kagoshima Bays. The phenomenon algal bloom, i.e., red tides was most likely driven by the eutrophication of coastal areas caused by effluent loading and aquaculture expansion **(Zohdi & Abbaspour, 2019)**. Noxious red tides are harmful to fish and invertebrates causing mass mortalities, particularly in intensive aquaculture in coastal area and increasing the negative impact on the aquaculture industry **(Imai *et al*., 2006)**.

Wastewater regulations are applied to areas where the degree of closure (C) is 1 or higher according to the Water Pollution Control Law, Japan (**International EMECS Center, n.d.)**. Among the 12 studied enclosed bays, higher C value (6.26) was found in Kagoshima Bay, which has a relatively small bay mouth width of 11km for a bay surface area of 1040km^2. On the contrary, lower C value (1.04) was found in Shizugawa Bay, which has a relatively large bay mouth width of 6.6km for a bay surface area of 46.8km^2. However, C also depends on the maximum water depth both in the bay and bay mouth. C values among the enclosed bays ranged from 1.04 to 1.48 in Miyagi, 1.08 to 1.81 in Mie and 1.2 to 6.26 in Kagoshima. National government has specifically established an environmental standard type in consideration of the situation of water area **(International EMECS Center, n.d.)**. Our studied bays are designated as "sea areas" and the environmental standard values, i.e., chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP) are assigned from 2 ≥ to 3 ≥ (mg/L), 0.2 ≥ to 0.3 ≥ (mg/L), and 0.02 ≥ to 0.03 ≥ (mg/L), respectively, in order to prevent water pollution and water quality management for aquatic environment conservation in "sea areas" **(International EMECS Center, n.d.)**.

3. Sustainability indicators and correlation analysis

Higher number of coho salmon aquaculture farms in Miyagi prefecture were found in Onagawa Bay compared to the area of bay, and width of bay mouth of Onagawa Bay was also smaller. Alternatively, the surface area and width of bay mouth of Shizugawa Bay were larger compared to the number of aquaculture farms. We found that, ΣI_2 value was higher in Onagawa Bay, followed by Ogatsu and Shizugawa Bays, and ΣI_3 value was higher in Shizugawa Bay, followed by Ogatsu and Onagawa Bays during FY 2018 and FY 2019, suggesting lower aquaculture sustainability, whereas C value of Ogatsu Bay (1.48) was comparatively higher than other 2 bays. Red tides occurrence was observed once (1 day) in Onagawa Bay during FY 2018, whereas no record of red tides was detected in Shizugawa and Ogatsu Bays. In FY 2019, red tides did not occur in the enclosed bays in Miyagi. The ΣI_2, and ΣI_3 values in 3 enclosed bays in Miyagi were decreased from FY 2018 to FY 2019, and red tides occurrences also decreased. Apart from 3 bays in Miyagi, 1 farm in Izushima area beside Ogatsu Bay had maximum I_2 values and most of the farms outside of the bay had comparatively higher I_2 values. In majority of aquaculture farms, I_2 of coho salmon aquaculture in Miyagi were decreased from FY 2018 to FY 2019. Therefore, nutrient load production from aquaculture should be considered for future sustainability and marine aquaculture development.

In Mie prefecture, I_2 values in the aquaculture farms located in bay areas were comparatively higher than that of the open water areas. The width of bay mouth of Gokasho and Owase Bays were smaller compared to the surface area of the other 3 bays. Conversely, the number of aquaculture farms in Owase Bay was comparatively higher. The ΣI_2 value was also higher in Owase Bay, followed by Gokasho, Kamisaki, Kata and Nie Bays; whereas, ΣI_3 value was higher in Owase Bay, followed by Gokasho, Kata, Kamisaki, and Nie Bays. C value in Gokasho Bay (1.81) was higher followed by Owase Bay (1.70). Red tides occurred thrice (total 22 days) and twice (total 36 days) in Owase and Gokasho Bays, respectively, during FY 2018, whereas once in Owase (11 days), Gokasho (1 day) and Nie (1 day) Bays during FY 2019. However, in Kamisaki and Kata Bays, red tides did not occur. In Owase Bay, ΣI_2 value was stable, but ΣI_3 value was slightly decreased from FY 2018 to FY 2019, and ΣI_2, and ΣI_3 values increased in Gokasho and Kamisaki Bays, while they were stable in Nie and Kata Bays. Duration of red tides occurrences in Mie also decreased in Owase and Gokasho Bays, whereas they increased in Nie Bay from FY 2018 to FY 2019.

Study in Kagoshima prefecture showed that, I_2 values in the farms of Nagashima area were comparatively higher than other yellowtail aquaculture. Although the Kagoshima Bay has larger area, but width of bay mouth is smaller. In addition, number of farms is higher in Kagoshima Bay in comparison with Nakakoshikiura, Yakiuchi, Kuji and Shinokawa Bays. The ΣI_2 value was at a maximum in Kagoshima Bay, followed by Kuji and Shinokawa, Yakiuchi, and Nakakoshikiura Bays, while ΣI_3 value was higher in Kagoshima Bay followed by Yakiuchi, Kuji and Shinokawa and Nakakoshikiura Bays. C value was also higher in Kagoshima Bay (6.26). Red tides occurred thrice (total 50 days) in Kagoshima Bay during FY 2018, and no record of red tides was detected in other bays. In FY 2019, red tides occurred once in both Kagoshima (11 days) and Nakakoshikiura (15 days) Bays, whereas it did not occur in Yakiuchi, Kuji and Shinokawa Bays. The ΣI_2, and ΣI_3 values decreased in Kagoshima Bay, while slightly increased in Nakakoshikiura Bay, and ΣI_2 value was stable, whereas ΣI_3 value increased in Yakiuchi, Kuji and Shinokawa Bays from FY 2018 to FY 2019. Duration of red tides also decreased in Kagoshima Bay, whereas increased in Nakakoshikiura Bay.

Correlation analysis indicated a statistically significant correlation between log ΣI_3 values and the degree of closure (C) across the bay, although I_3 does not directly take the degree of closure into account. It suggested that enclosed bays with higher C have consequently more aquaculture impacts at longer distances from the bay mouth. This suggests that a simple indicator, I_3, can be a useful indicator for assessing aquaculture sustainability. The fact that there was also a positive correlation between log ΣI_3 values and the red tides occurrence in FY 2018 indicates that nutrient load and farms' location in enclosed bay may have an impact on red tide occurrence. However, in FY 2019, the frequency of red tide outbreaks was lower than in FY 2018, except in Nakakoshikiura Bay, and no correlation with log ΣI_3 values was observed. If nutrient load and farms' location affects the frequency of red tide occurrence in enclosed bay, it may be limited to years when red tide is more likely to occur due to other factors.

Considering nutrient load per aquaculture farm, I_2 values could serve as indicators for assessing sustainability of coho salmon, red seabream, yellowtail, and bluefin tuna aquaculture outside of the enclosed bays as nutrient load production significantly related with environmental consequences. Alternatively, ΣI_2 and ΣI_3 values could be indicators for long-term sustainability assessment of marine aquaculture in enclosed bays. Higher values for $\Sigma I_{2,}$ and ΣI_3 in enclosed bays suggested lower aquaculture sustainability and higher possibility of red tides occurrences. Therefore, Shizugawa and Onagawa Bays in Miyagi prefecture, Owase, and Gokasho Bays in Mie prefecture and Kagoshima Bay in Kagoshima prefecture may have the possibility to be affected by the risk of environmental consequences in marine aquaculture.

4. Study limitations and future directions

We conducted the study focusing on the 4 major aquaculture species of 12 enclosed bays in 3 different prefectures based on the available data. Other fed and non-fed aquaculture species should be considered for overall sustainability analysis. Non-fed aquaculture species, i.e., oyster, scallop etc. are known to have a much lower nutrient load than fed aquaculture **(Oita *et al.*, 2015)**. Absorption of phytoplankton that uses nutrients excreted from cages in integrated multi-trophic aquaculture (IMTA) can further reduce the load from cultured fish to surrounding water **(Abo *et al.*, 2013)**. In addition, nutrient inputs from rivers such as domestic wastewater should also be considered.

Number of identified aquaculture cages from satellite images can be varied because some cages are kept below in water and not all the cages are used for aquaculture purposes at the final harvest. Mean depth of cages and aquaculture farms can also be varied. Hence, actual I_1, I_2, and I_3 values can be diverse from farms to farms. In this regard, detailed field study of the aquaculture farms should be needed for the improved applicability of the indicators.

Red tides have significance on the sustainability of marine aquaculture, but the other parameters such as nutrients and oxygen concentrations may be the alternatives of the index. The nutrient load from aquaculture production that has an impact on red tides was taken into account, but red tides are also influenced by other environmental parameters, i.e. light intensity, temperature, salinity etc. in marine environment **(Genitsaris *et al*., 2019; Wells *et al*., 2020)**.

Sustainability indicators including all the relevant environmental factors for red tides occurrences should be included for predicting effectiveness of the indicators in long-term sustainability analysis. To assess environmental sustainability and economic feasibility of ocean utilization technologies, the Inclusive Impact Index “Triple I” can be used based on ecological footprint and environmental risk assessment concepts **(Otsuka *et al*., 2018)**.

We did not suggest any threshold values of the sustainability indicators. However, threshold values of these indicators could be useful for proper resources utilization. Therefore, further analysis in overall aquaculture areas and longer term analysis could be included later on for the feasibility of the sustainability indicators that we proposed.

CONCLUSION

Increasing aquaculture productivity is one of the biggest challenges in terms of aquatic environmental sustainability. Duration of red tides occurrence in enclosed bays signified that the numerous issues should be addressed and accomplished for aquaculture sustainability. We emphasized on the improvement of research design by more thorough field work to recommend optimum aquaculture production. Baseline findings of this research on marine aquaculture can be helpful for estimating farms’ level aquaculture production and associated nutrient load to predict future optimum seafood production from ecologically balanced aquatic environment.

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APPENDIX

Table A.1 Occurrence records of red tides in different enclosed bays during FY 2018 to FY 2019

Prefectures	**FY 2018**		**FY 2019**	
	Bays	**Date of occurrences* (Month/Day)**	**Bays**	**Date of occurrences* (Month/Day)**
Miyagi**	Onagawa	8/10		
Mie***	Gokasho	7/6 to 8/9	Gokasho	12/16
		11/27	Nie	8/27
	Owase	5/21 to 6/1	Owase	7/2 to 7/12
		8/21 to 8/29		
		12/5		
Kagoshima****	Kagoshima	5/9 to 5/10	Nakakoshikiura	5/11 to 5/25
		10/29 to 11/9	Kagoshima	10/11 to 10/21
		2/27 to 4/3		

* Brief data of red tides are collected from the prefectural websites.

** Miyagi Prefectural Government. Red tide information. https://www.pref.miyagi.jp/soshiki/suikisei/akasio.html (Accessed on: 11 September, 2021).

*** Mie Prefectural Government. Red tide in the coastal waters of Mie Prefecture. https://www.pref.mie.lg.jp/suigi/hp/78550017262.htm (Accessed on: 11 September, 2021).

**** Kagoshima Prefectural Fisheries Technology and Development Center. Kagoshima Prefecture Red Tide Information. http://kagoshima.suigi.jp/akashio/newHP/index.html (Accessed on: 11 September, 2021).

Table A.2 The degree of closure of different enclosed bay areas

Prefectures	**Enclosed Bays**	**Surface Area (km^2)***	**Bay Mouth Width (km)***	**Maximum Water Depth in the Bay (m)***	**Maximum Water Depth at Bay Mouth (m)***	**Closure index (*C*)***
Miyagi	Shizugawa	46.8	6.6	54	54	1.04
	Ogatsu	19.82	3.01	46	46	1.48
	Onagawa	12.1	2.5	36	36	1.39
Mie	Gokasho	22.2	2.6	27	27	1.81
	Nie	12.24	3.25	58	58	1.08
	Kamisaki	9.75	2.68	53	53	1.17
	Owase	19.65	2.6	58	58	1.7
	Kata	12.6	2.82	82	82	1.26
Kagoshima	Kagoshima	1040	11	237	111	6.26
	Nakakoshikiura	8.47	2.42	60	60	1.2
	Yakiuchi	25.76	2.53	84	84	2.01
	Kuji and Shinokawa	11.17	2.79	76	76	1.2

* International EMECS (Environmental Management of Enclosed Coastal Seas) Center, n.d. https://www.emecs.or.jp/info (Accessed on: 7 August, 2021).

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