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Sustainability Assessment of Marine Aquaculture considering Nutrients Inflow from the Land in Kyushu Area

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Abstract: The nutrient load generated by excessive aquaculture farms leads to self-pollution around water, which destroys aqua-environment, and further leads to a decline in aquaculture production. The purpose of this study is to propose an index to assess the sustainability of inshore aquaculture in Kyushu area, considering nutrient loads from land and farms. The number and size of fish cages identified from Google satellite imagery are used to calculate annual fish production, which is then converted into annual loads of total nitrogen and total phosphorus. The pollutant load factor method is applied to calculate the land nutrient inflow. An index, including nutrient load from land and farms, bay area, water depth and distance from farms to bay, is proposed. The results show that for most of the cultured bays in Kyushu, the nutrient load from the farm is more than that from the land inflow. The bay with higher index value has a higher possibility of red tide occurrence and lower sustainability for aquaculture. Among which, location of fish farms, total nitrogen and total phosphorus loading are key factors impacting water quality within the bays.

Keywords: marine aquaculture; sustainability assessment; nutrient inflow load; pollutant load factor method

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1. Introduction

Marine aquaculture has huge potential to meet the increasing food demand due to the advantages of relatively few spatial conflicts [1]. With the development of marine aquaculture, intensive aquaculture, the impact of residual bait and excrement from fishing farms on the surrounding environment has been continuously reported [2–4]. Currently the main marine aquaculture is carried out inshore [5], where the water exchange capacity is weaker than open ocean. The pollution from fish farms not only decreases the water quality around the farms, but also affects the bottom organisms. The deterioration of the environment around the fish farm can reduce marine biodiversity and cause fish deaths, decreasing fishery production. Therefore, a suitable cultural density within the environmental carrying capacity should be understood.

Many research and political treatments have been carried out to estimate the carrying capacity and keep the production within carrying capacity. Numerical simulation models of hydrodynamics and ecosystems in coastal waters have been developed to create carrying capacity estimations [6–9]. However, numerical simulation always focuses on specific farm scale, making it difficult to estimate the culture capacity and doing comparative study in bay-scale. A sealing index of a bay [10] was proposed to evaluate the closure of the offshore bays of Japan, which had experienced frequent red tides since the 1960s. This index evaluated the water exchange ability by non-dimensioning the surface area of the water, the width of the bay mouth, the average water depth of bay mouth and inner bay. The location of the farms in the bay also affects the dispersion of emissions from the farm. Embayment degree index [11] was proposed considering topography and farm location to evaluate the capacity of seawater exchange and the pollutant diffusion of culture bays.

In addition to topography and farm location in bays, nutrient load from farms and land is also important factor affecting the environmental capacity to the nutrient before reaching the open ocean to be diluted [12–14]. However, few studies compare the impacts of water exchange, topography, nutrients load from farms and land on the environment in bays. The objective of this study is to propose an index including bay topography, farm location and inflow of nutrient loads from farms and land to assess environmental capacity in bay-scale. The research objective of this study can be divided into three sub-objectives: (1) Building aquaculture production estimation model since bay-scale production data is unavailable currently from the governmental statistics, to calculate the nutrient load from fish farm; (2) Establish land nutrient load calculation system; (3) Propose an appropriate assessment index.

2. Materials and Methods

2.1. Study Area

The study area of this research located in Kyushu region of Japan, and the target area are the bays where fish aquaculture carried out (Figure 1). Based on data availability, the period of this study is 2018.

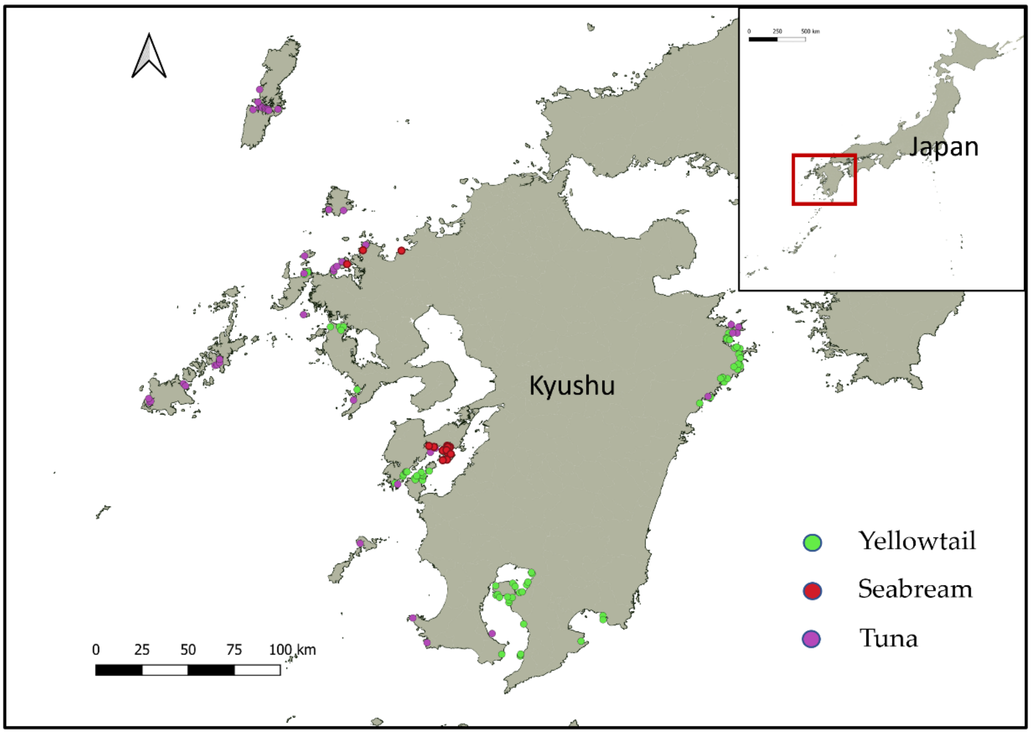


Figure 1. Study area map showing the distribution of fish farms where yellowtail, tuna and seabream are cultured.

The Kyushu region is located at the southwestern tip of Japan and is the third largest of Japan's five main islands, between latitudes 30°58′16″ N and latitudes 34°03′43″ N and longitudes 128°12′54″ E and 132°43′41″ E. Kyushu Island is surrounded by the sea on all sides and is a warm region with large warm oceanic currents such as the Kuroshio Current and the Tsushima Current. In addition, it has a complicated coastline with many remote islands and peninsulas, and various coastal fisheries and aquaculture are carried out. According to government statistics [15], the production of aquaculture in the Kyushu region in 2018 was 268,242 tons, accounting for about 30% of the national total. Among them, the main fish species that are farmed are yellowtail, tuna and seabream (Figure 1), the production are 93,994 tons, 10,266 tons and 13,125 tons, and a rate of 37%, 58% and 22% of the total production in Japan, respectively. A circle represents a fish farm which has multiple cages culturing single or several fish species. The fish farm is licensed as the demarcated fishery right. Sustainable Aquaculture Production Assurance Act was established in 1999 to take measures to promote the improvement of the fish farm to be performed by Fisheries Cooperative Association, whereas such measures have not been taken for a bay that includes several fish farms.

Algal blooming, called as red tide, has been frequently reported in the Kyushu area. A total of 69 red tide events were reported in 2018 [16]. The number of days of red tide lasting in a year was 1236, and the average duration of each red tide was 18.2 days. Of the 69 red tides reported, nine caused damage to fisheries. Including the suffocation of farmed fish, the damage to the fishery amounted to about JPY 30 million. In the present study, fish production is calculated for all the fish farms, whereas the other analyses are carried out for the main 12 bays which monitor the occurrence of red tides.

2.2. Annual Fish Production Estimation

2.2.1. Fish Production Calculation Model

This study aims to analyze in bay scale and the fish production of each bay is necessary. However, the existing government statistics only have production amount of each prefecture. Therefore, this study proposes a formula [17,18] for estimating the annual production of farmed fish in the bay. The formula of annual fish production of each farm is derived from a previous study [19], in which the production per year was calculated by dividing the total farm output by the number of years between stocking and harvest. Considering the continuity of fishery farming, the annual fish production is defined as the ratio of total fish production to stock cycle, shown as

$$p = \sum\nolimits_{s=1}^{m} \left(\frac{P_s}{T_s} \right) \tag{1}$$

where p (ton) is the annual production of a fish farm, T_s (year) is the period between stocking and harvest of a specific fish species, the subscript s represents different species of fish and P_s (ton) is the corresponding total output during T_s. Considering that some farms stock more than one fish species, m denotes species number in a farm, annual production of a farm is the sum of annual production of each species.

Total production P_s of each species during T_s is calculated by

$$P_s = \sum\nolimits_{1}^{n} (W_s \times R_s) \tag{2}$$

where W_s (ton) is the weight of seawater inside each fish cage, which is calculated by

$$W_s = \rho \times V_s \tag{3}$$

V_s (m^{-3}) means the volume of fish cage and ρ (ton m^{-3}) is the density of seawater. The area of fish cage is measured from satellite images and mean depth of a cage is assumed 8 m for yellowtail and seabream, and 10 m for tuna. R_s (%) is the stock rate of species, which means weight ratio of stocked fish and seawater inside the cage when the fish are available for harvest. n denotes cage number of a species in a farm. Table 1 shows the parameter value of each species, the values of which are based on interviews with local farmers.

Table 1. The stock rate and harvest period of Yellowtail, Tuna and Seabream.

Parameter	Yellowtail	Tuna	Seabream
R_s	3.0%	0.3%	3.0%
T_s (year)	2.0	2.5	2.0

2.2.2. Fish Cage Detection

To get the number and size of fish cages used to calculate fish production, the location of the fish farm and the type of fish species are figured out by Google Earth Pro software, according to the Fish Farm Survey Database [20] and the MDA Situational Indication Linkage [21]. Then the cage number, shape and size are identified based on the historical satellite image of 2018 in Google Earth Pro software. Figure 2 shows one case of fish cages detected. A part of cages is detected by the image analysis, and the others are detected manually.

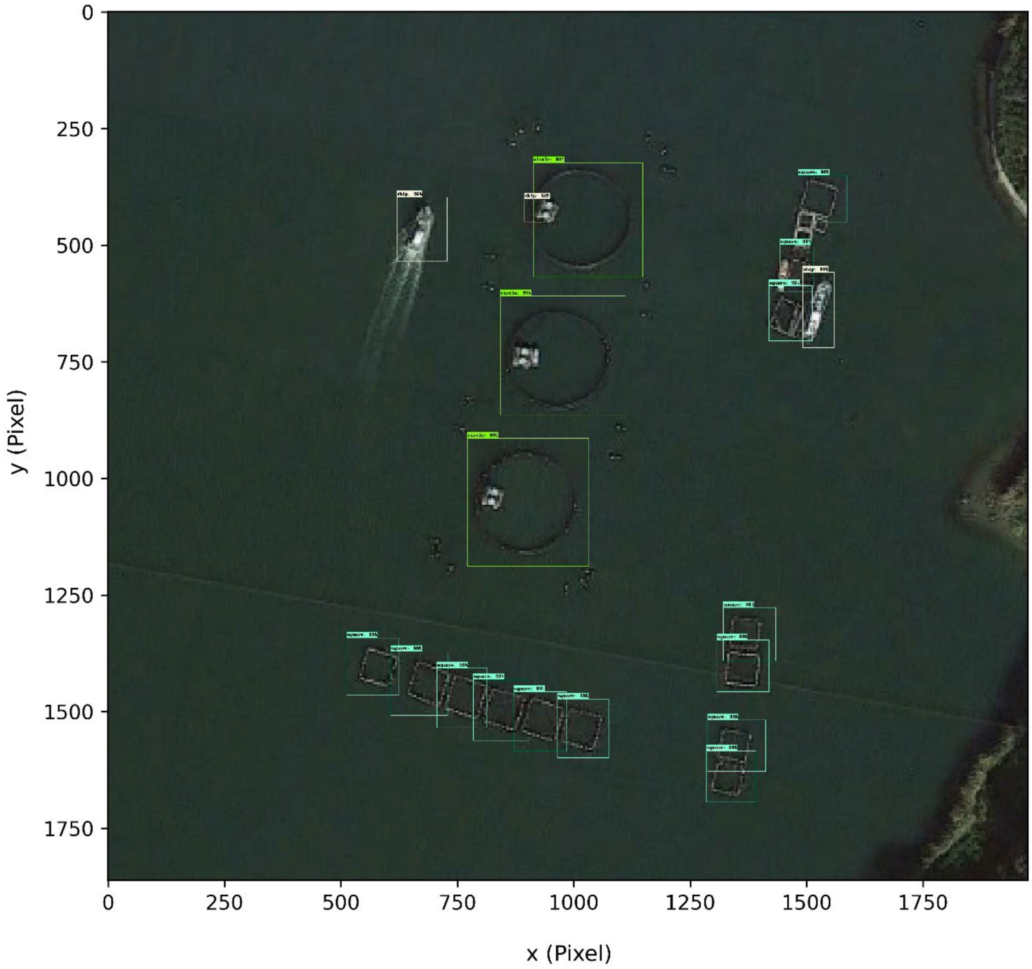


Figure 2. An example of fish cage detected. The square cages are used for culturing yellowtail or sea bream, and the circular cages are used for culturing tuna.

2.3. Calculation of Nutrient Load from Fish Farm

Waste from farms includes feed loss, fish excreta and metabolites. With the improvement of feed quality and feeding technology, the feed wastage percentage is lower than 5% [22–24]. The Norwegian salmon farmers claim that feed loss in modern salmon production, using camera assisted feeding control and acoustic registration of lost feed pellets, is negligible and that there are no economic and environmental incentives to further reduce feed loss [25]. The major wastes come from metabolites, following fish excreta. The nutrients of total nitrogen (TN) and total phosphorus (TP) are considered here. The calculation flow of nutrient load from farms in this study is shown in Figure 3.

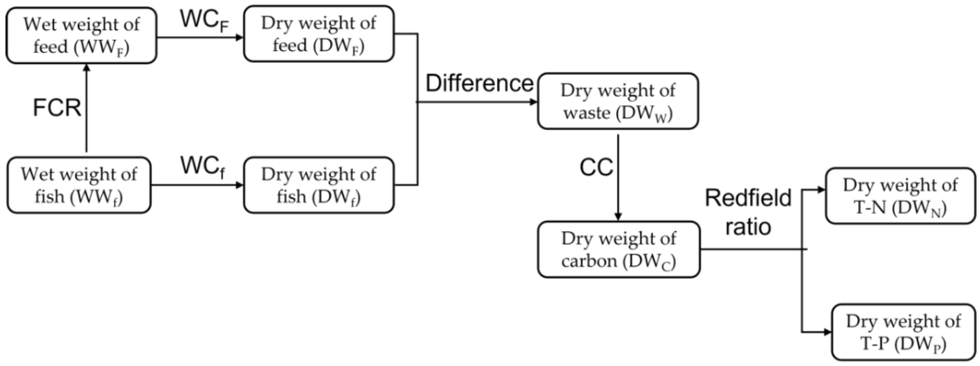


Figure 3. The calculation flow of nutrient load from fish farm.

The wet weight of fish (WW_f; ton) is multiplied by the feed conversion ratio (FCR_s) to obtain the wet weight of feed (WW_F; ton).

$$WW_F = WW_f \times FCR_s \tag{4}$$

The dry weight of feed (DW_F; ton) and the dry weight of fish (DW_f; ton) are calculated according to the water content in feed (WC_F) and the water content in fish (WC_f) by

$$DW = WW \times (1 - WC) \tag{5}$$

The parameter values corresponding to each type of fish are different and are listed in Table 2. The water content in feed is determined so that the compounded feed is used for culturing yellowtail and seabream, and the raw fish is used for culturing tuna. The dry weight of the feed minus the dry weight of the fish is the dry weight of waste (DW_W; ton)

$$DW_w = DW_F - DW_f \tag{6}$$

Table 2. Parameter's value of fish farm nutrient load calculation.

Parameter	Yellowtail	Tuna	Seabream
FCR	2.5	10	2.5
WC_f	10%	75%	10%
WC_F	75%	75%	75%

The carbon content (CC) of the discharged waste was set at 40%. Calculate the dry weight of carbon (DW_C; tC) in the discharged waste by

$$DW_C = DW_w \times CC \tag{7}$$

The components ratio of nutrient released from fish farm changes depending on the species and cultured location [9,26,27]. Basically, the feed is made of zooplankton and smaller fish that eats planktons, partly of vegetable protein. Though the contents of nitrogen and phosphorus in the feed have a variety, they are similar to the Redfield ratio on average. Therefore, the dry weight of nitrogen and phosphorus (DWN; tN, DWP; tP) in the waste discharged from the farms over a year is calculated according to the Redfield ratio in this research.

The nutrient load is calculated from a cage for each species, and then summed to estimate the total nutrient load in a fish farm which includes multiple cages and several species. Finally, the total nutrient load is estimated for a bay which includes several fish farms.

2.4. Calculation of Nutrient Load from Land Inflow

Since the environmental carrying capacity of bays on aquaculture is affected by nutrient concentration, nutrient loading from land is an important factor needed to be considered. The commonly used method for estimating land inflow load is to calculate river inflow load based on river flow and observational water quality data [28,29]. This method is suitable for large rivers with abundant observational data available. For smaller rivers, flow and water quality data are usually not easily obtained, so this method does not work. In the Comprehensive Plan Survey of Sewerage Maintenance by Basin (CPSSMB) [30] conducted by Ministry of Land, Infrastructure, Transport and Tourism of Japan, the emission load amount of the entire target area is calculated and evaluated using the pollutant load factor method. Research calculating river inflow from different sources using pollutant load factor method also exist [31–35]. The pollutant load factor method is to multiply the set discharged load unit by the corresponding cardinal number of each load source to obtain the total load of each source. This method is not limited to large rivers and can calculate the nutrient load discharge of rivers of various sizes. It is also possible to estimate historical emissions and predict future changes.

This research uses the pollutant load factor method to estimate the nutrient load from land inflow to the bays. Considering the scale and geographic characteristic of the study area, it is assumed here that all discharged nutrient loads flow to the bay since the watershed is not so large and the water with discharged nutrient flows promptly into the sea. The calculation process is as follows (Figure 4).

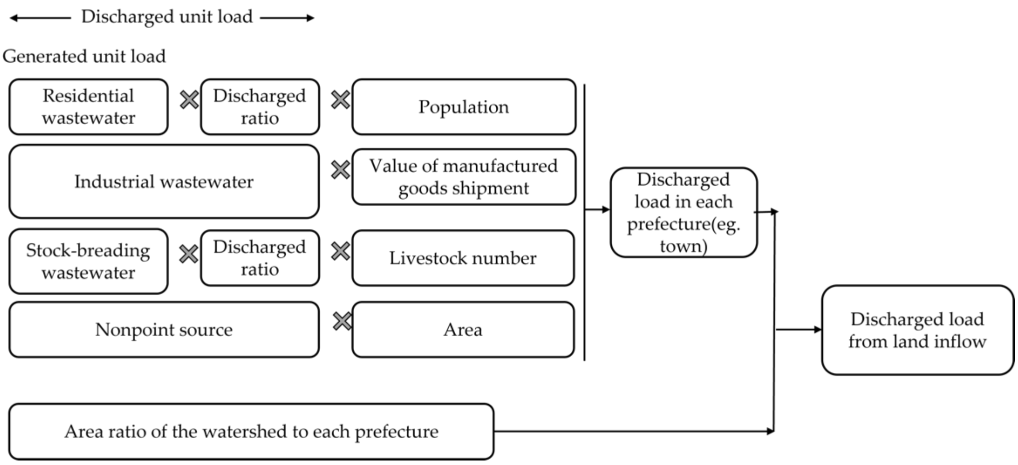


Figure 4. The calculation flow nutrient load from land inflow.

The original generated load units of the four types of sources used here are the set value in CPSSMB [30]. The discharged unit of domestic wastewater is the generated unit of occurrence multiplied by the discharge rate, and the discharge rate differs depending on the method of sewage treatment [36]. This research is based on the 2015 population census [37] and the 2018 sewerage population penetration rate [38] to calculate the total nutrient load discharged from residential wastewater. The discharged load units of animal stock-breeding wastewater are the generated unit of occurrence multiplied by the discharge rate, and the discharge rate varies depending on the species of animals [36]. The cardinal number is the numbers of animal from the governmental statistical data [39]. The discharged load unit of industrial and non-point source used here is also the set value in CPSSMB [30]. The cardinal number of industrial wastewater is the value of manufactured goods shipment from the governmental statistical data [40]. In the non-point source load, four types of land use areas of rice fields, agricultural land, forests, urban areas are considered, and the data come from the land use mesh data of the Ministry of Land, Infrastructure, Transport and Tourism of the Japanese government [41].

The watershed boundary of each bay is obtained through GIS (ArcGIS, ESRI) software, based on the watershed boundary data and elevation mesh data of the Ministry of Land, Infrastructure, Transport and Tourism [42,43]. Calculate the area proportion of the watershed area in each prefecture by GIS software. The sum of the discharge load for each prefecture multiplied by the watershed area ratio is the discharge load for each bay from the corresponding watershed.

2.5. Assessment Index

This study proposes three different assessment index (Equations (1)–(3)) [17,18], to analyze the impact of different factors on the water environment, considering the topography of the bay, the location of the farm in the bay and the nutrient load from both the farm and land.

$$I_1 = \frac{Q}{A * H} \tag{8}$$

$$I_2 = \frac{Q * D}{A * H} \tag{9}$$

$$I_{3-1} = \frac{N_{L,tN} * N_{F,TN}}{A * H} * D \qquad I_{3-2} = \frac{N_{L,tP} * N_{F,TP}}{A * H} * D \tag{10}$$

As shown in Figure 5, Q (ton), A (km^2), H (m) is the total fish production, the area and the mean water depth of the bays, respectively. D (m) is the mean distance from fish farms to bay mouth, which is defined as the line between the tips of peninsulas. $N_{L,TN}$ (TN) and $N_{L,TP}$ (TP) is total nitrogen and total phosphorus from land inflow. $N_{F,TN}$ (TN) and $N_{F,TP}$ (TP) is the total nitrogen and total phosphorus from fish farms in each bay.

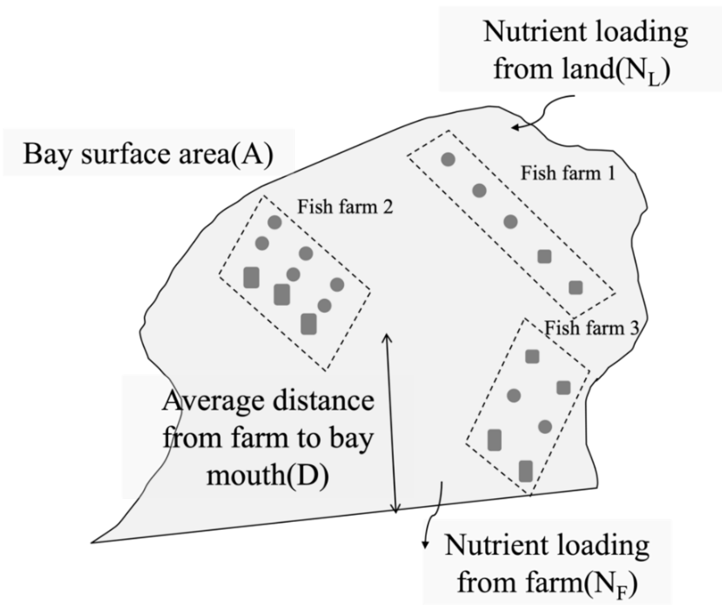


Figure 5. Illustration of parameters in the index. This is a case of bay with 3 fish farms within. D is the mean value of the distance from farm 1, farm 2 and farm 3 to the bay mouth. N_F is the total load from farm 1, farm 2 and farm 3.

3. Results and Discussion

3.1. Fish Production Calculation

3.1.1. Fish Cages

To calculate the nutrient load from farms within each bay, the annual production of farmed fish within the bay was calculated, identified from Google satellite image. Tables 3–5 are the statistics of the shape, size and number of yellowtail, tuna and seabream cages in Kyushu. Yellowtail has the largest cage number and cultured area in Kyushu, with a total of 7052 and 2935.7 ha. Most of them are square cages with a side length of about 8–15 m, the circular cage is larger in size, with a diameter of about 15–50 m. Tuna fish cage and cultured area in Kyushu is the least compared to the other two fish, with a total of 874 and 204.8 ha. The cage size required for Tuna is larger, with a minimum length of 15 m and a maximum of 85 m. Seabream has 983 cages in Kyushu, most of which are square cages with a side length of about 6–12 m. Similar to the yellowtail case, the size of the circular cage is larger, with a diameter of about 12–30 m.

Table 3. Fish cage and cultured area statistics of Yellowtail in Kyushu.

Shape	Size (m)			Number	Cultures Area (ha)
	Length	Diameter	Depth		
Square	8–15		8	6676	
Rectangular					2935.7
Circular		15–50	8	376	

Table 4. Fish cage and cultured area statistics of Tuna in Kyushu.

Shape	Size (m)			Number	Cultures Area (ha)
	Length	Diameter	Depth		
Square					
Rectangular	15–85		10	304	1263.2
Circular		15–50	10	570	

Table 5. Fish cage and cultured area statistics of Seabream in Kyushu.

Shape	Size (m)			Number	Cultures Area (ha)
	Length	Diameter	Depth		
Square	6–12		8	866	
Rectangular					204.8
Circular		12–30	8	117	

3.1.2. Fish Production Calculation

The production of Kyushu's yellowtail, tuna and seabream in 2018 were 87,559.27 tons, 9688.57 tons and 12,108.01 tons, respectively, accounting for 63.34%, 54.92% and 19.93% of Japan's national output, respectively. Figure 6 shows the fish production distribution of 12 main cultured bay areas in Kyushu.

The calculated production of this study was compared with government statistics production (Table 6). Compared with the Marine Aquaculture Production Statistics of 2018, the estimated yellowtail production of Kyushu area is 6.84% lower than the statistical production, the calculated tuna production is 5.62% lower than the statistical production and seabream is 7.75% lower than the statistical data.

One of the main reasons for the deviation of production data in Table 6 is that the statistics of the Ministry of Agriculture, Forestry and Fisheries are not completely equal to the actual aquaculture data. In the statistical process, due to the protection of commercial secrets, some fishery information is not disclosed. Second, in the calculation of production in this study, the number of fish cages is calculated based on satellite images. In fact, during the breeding process, some fish farmers will sink the cages below the water surface to avoid the impact of typhoons and red tides. In this case, the number of cages captured by satellite images is less than the numbers actually farmed, so the calculated production is also lower than the actual amount.

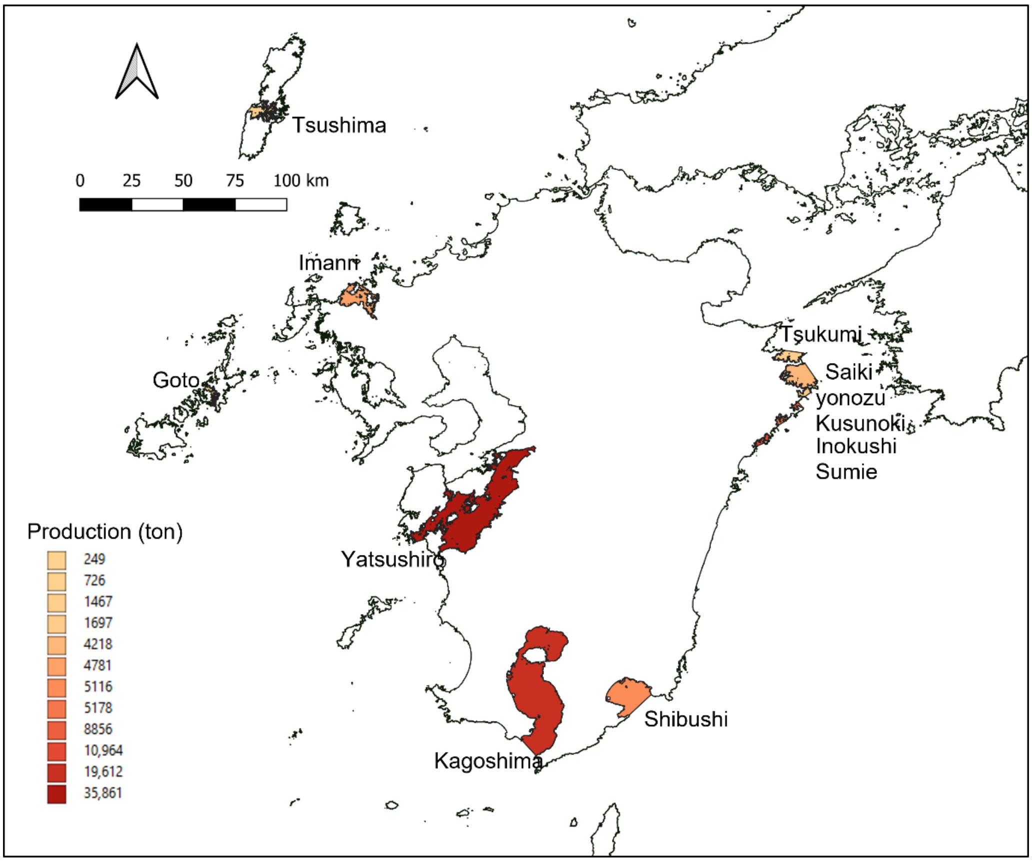


Figure 6. Fish production distribution of 12 main cultured bay areas in Kyushu.

Table 6. Fish production calculated in this research and the government statistics in 2018.

Species	Yellowtail	Tuna	Seabream
Calculated data (ton)	87,559.27	9688.57	12,108.01
Governmental Statistics (ton)	93,994.00	10,266	13,125.00
Deviation	−6.84%	−5.62%	−7.75%

3.2. Nutrient Load Analysis

3.2.1. Nutrient Load from Fish Farm and Land Inflow

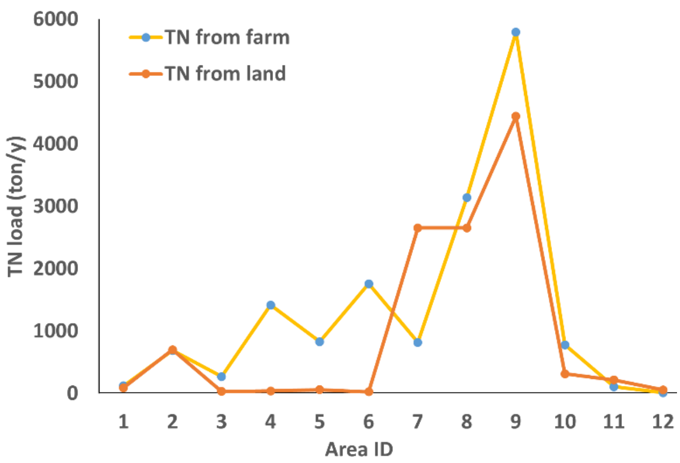
According to the data available and production scale, nutrient load from fish farms and land inflow of 12 main cultured bay areas is calculated as shown in Table 7. Bay areas of Yatsushiro and Kagoshima ranked the top two in terms of annual emissions from both fish farm and land inflow.

Table 7. Nutrient load amount from fish farms and land inflow.

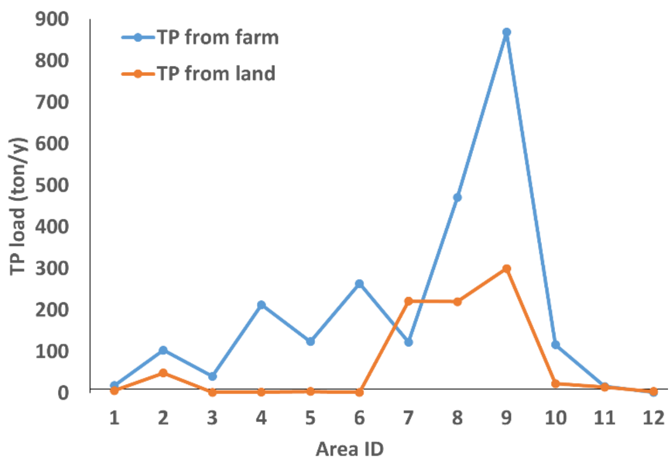
ID	Bay Areas	TN Load from Farm (ton/y)	TP Load from Farm (ton/y)	TN Load from Land (ton/y)	TP Load from Land (ton/y)
1	Tsukumi	122	18.3	92	6.4
2	Saiki	690	103.5	702	48.5
3	Yonozu	272	40.7	32	2.2
4	Kusunoki	1417	212.5	41	2.8
5	Inokushi	829	124.3	60	4.2
6	Sumie	1760	263.9	27	2.2
7	Shibushi	819	122.8	2656	221.4
8	Kagoshima	3139	470.8	2655	220.2
9	Yatsushiro	5792	868.9	4444	300.0
10	Imanri	778	116.7	316	23.1
11	Tsushima	109	16.3	217	14.8
12	Goto	14	2.1	58	4.0

3.2.2. Comparation between the Nutrient Load from Fish Farm and Land Inflow

Of the 12 counted bays in the Kyushu area, eight of them have a greater amount of TN released from farms than from land (Figure 7) and all of them have a greater amount of TP released from fish farms than land inflow (Figure 7). The Comprehensive Plan Survey of Sewerage Maintenance by Basin has been conducted from 1970, regulating the discharge of terrestrial nutrients to improve the water environment of the bay. Currently the nutrient load from land inflow has been greatly reduced. It is assumed in this study that all discharged nutrient loads flow to the bay and the water with discharged nutrient flows promptly into the sea. The amount of nutrient load from land inflow maybe less actually. On the contrary, the nutrient load release from inshore aquaculture has become a factor that cannot be ignored. Water quality observation stations, which are currently mainly set near the estuary, should also be considered near the fish farm. It should be noted that the supply of nutrients from atmosphere, sea bottom, and the outer sea was ignored in the present study. In particular, the nutrients release from the sea bottom may have ineligible effects on the nutrients balance in the bay when the water around the sea bottom is hypoxic.



(**a**)



(**b**)

Figure 7. The comparations between the TN from fish farm and land inflow (**a**), and the comparations between the TP from fish farm and land inflow (**b**). The numeric labels on the *X*-axis represent the ID of the bay areas as shown in Table 7.

3.2.3. Discharged Nutrient Load Ratio by Source from Land Inflow

For nutrient load from land inflow, the proportions of TN and TP amount from different sources were analyzed (Figure 8). Among the four discharge sources, TN and TP discharged from residential wastewater and non-point source accounted for the main part. This study used the proportion of the area of the watershed in each prefecture to calculate the nutrient load of the watershed, that means, assuming that the population, animal stocking, industry and non-point sources are evenly distributed in each prefecture. However, in fact, the geographical distribution of these sources is not even. Therefore, the refinement of the discharge load calculation cell can improve the accuracy of the calculation.

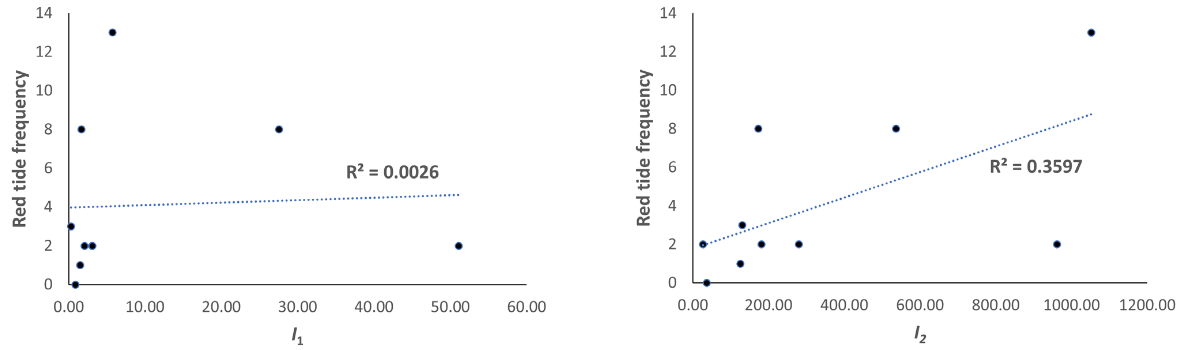
(**a**) (**b**)

Figure 8. Discharged nutrient load ratio by source from land inflow for TN (**a**) and TP (**b**). The numeric labels on the *Y*-axis represent the ID of the bay areas as shown in Table 7. RE is residential source. IN is industrial source. SB is stock-breading source and NON is non-point source.

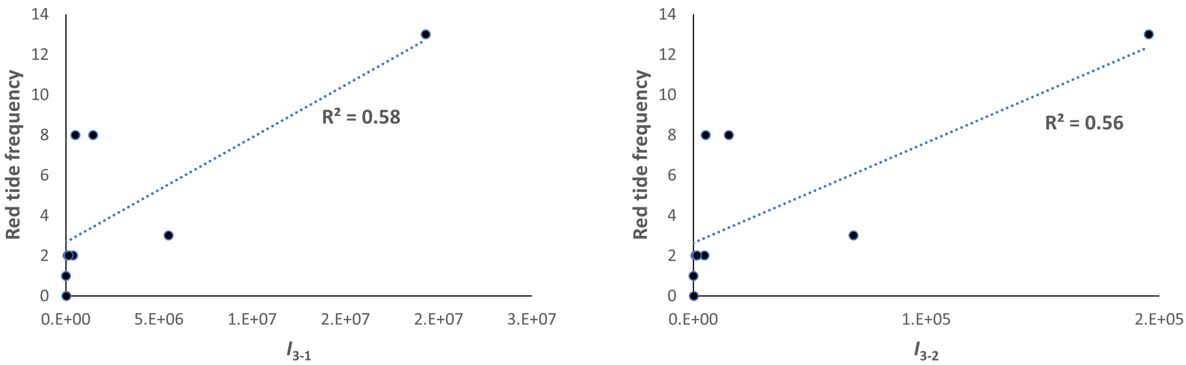
3.3. Assessment Index

3.3.1. Correlation Analysis

To test the performance of the assessment index and analyze the impact of different parameters on environmental problems, the correlation analysis between index I_1, I_2, I_3 and the water quality problem is performed. Based on the availability of data, the frequency of red tide occurrence reported in Kyushu area in 2018 is used as a representative of water quality problems. The correlation analysis results are shown in Figure 9.



(**a**) (**b**)



(**c**) (**d**)

Figure 9. Correlation analysis of I_1, I_2, I_3 and red tide frequency. Subfigures (**a**–**d**) are correlation analysis between I_1, I_2, $I_{3\text{-}1}$, $I_{3\text{-}2}$ and red tide frequency.

Index I_1 contains the annual production, area and water depth of the bay. Index I_2 added the distance from the farm to the bay mouth (D) compared to Index I_1. The comparison of (a) and (b) in Figure 9 shows that the distance between the farm and the mouth of the bay maybe an important factor affecting water quality. The location of the farm should be considered in aquaculture planning. Whereas the residence times and water exchange rates also depend on the current velocity. The physical parameters such as mean current velocity and the rate of exchange water may should be an alternative to the distance from the farm to the bay mouth in the future work. Anyway, the exchange of water seems to be an important factor for sustainability.

Index I_3 replaces fish production in index I_2 with TN ($I_{3\text{-}1}$) and TP ($I_{3\text{-}2}$) loads from farms and land inflow. The value of parameters included in I3 are listed in Table 8, except the TN and TP loading from fish farms and land inflow listed in Table 7.

Table 8. Index value of I_3 and parameters information.

ID	Bays Name	Area (km^2)	H (m)	D (km)	$I_{3\text{-}1}$	$I_{3\text{-}2}$	Red Tide Frequency
1	Tsukumi	69.7	20.9	4127	31,749	331	0
2	Saiki	176.5	19.4	10,387	1,469,135	15,225	8
3	Yonozu	26.4	21.0	5932	92,989	959	2
5	Inokushi	20.4	9.2	1947	515,711	5415	8
6	Sumie	24.1	9.4	1882	394,701	4824	2
8	Kagoshima	1302.1	50.7	43,740	5,521,820	68,695	3
9	Yatsushiro	1200.0	20.4	18,332	19,276,589	195,195	13
10	Imanri	166.9	17.5	1300	109,432	1200	2
11	Tsushima	84.2	16.7	8963	150,168	1536	2
12	Goto	27.8	18.1	8457	13,341	138	1

I_3 has positive relation with red tide occurrence frequency with coefficient of determination R^2 of about 0.6. It shows that bay with higher value of I_3 has higher possibility of red tide occurrence and lower sustainability for aquaculture. On the one hand, the total nutrient load from the farm is a better indicator of the impact of aquaculture on water quality than the fish production. As the amount of waste released per unit weight of fish production is different for different species of fish. In addition, the nutrient load from land inflow should also be considered when assessing the environmental capacity of the bay.

Depending on Figure 9, the correlation coefficient of $I_{3\text{-}1}$ and $I_{3\text{-}2}$ with the red tide frequency strongly affected by the point of Yatsushiro bay. However, Yatsushiro bay is very important in Kyushu area with the largest amount of fish production and seriously red tide problem, which cannot be ignored. Since only 10 bays are analyzed in this research, the dataset currently is not big enough, the correlation coefficient is easier to be affected by any point. In the future, the study area will be enlarged to whole cultured bays in Japan. More datasets will be included to analyze the performance of the assessment index.

The red tide frequency was selected as an indicator of eutrophicated pollution in the bay. However, the duration of the red tide occurrence was not taken into account in the present study. Additionally, red tides are observed visually so this indicator is not quantitative. The other indicators such as the concentration of nutrients in the sea should be considered for the sustainability analysis in the future.

3.3.2. Sustainability Analysis

Through the previous verification, the value of the sustainable assessment index I_3 has a significant positive correlation with the occurrence frequency of red tides. The higher the index value, the higher the possibility of red tide occur. Red tides lead to reduction of dissolved oxygen in water bodies, which can cause fish suffocation and reduce production. Therefore, areas with higher evaluation index values are less sustainable for marine aquaculture. Figure 10 shows the distribution of evaluation index values for the 12 major aquaculture bays in the Kyushu region.

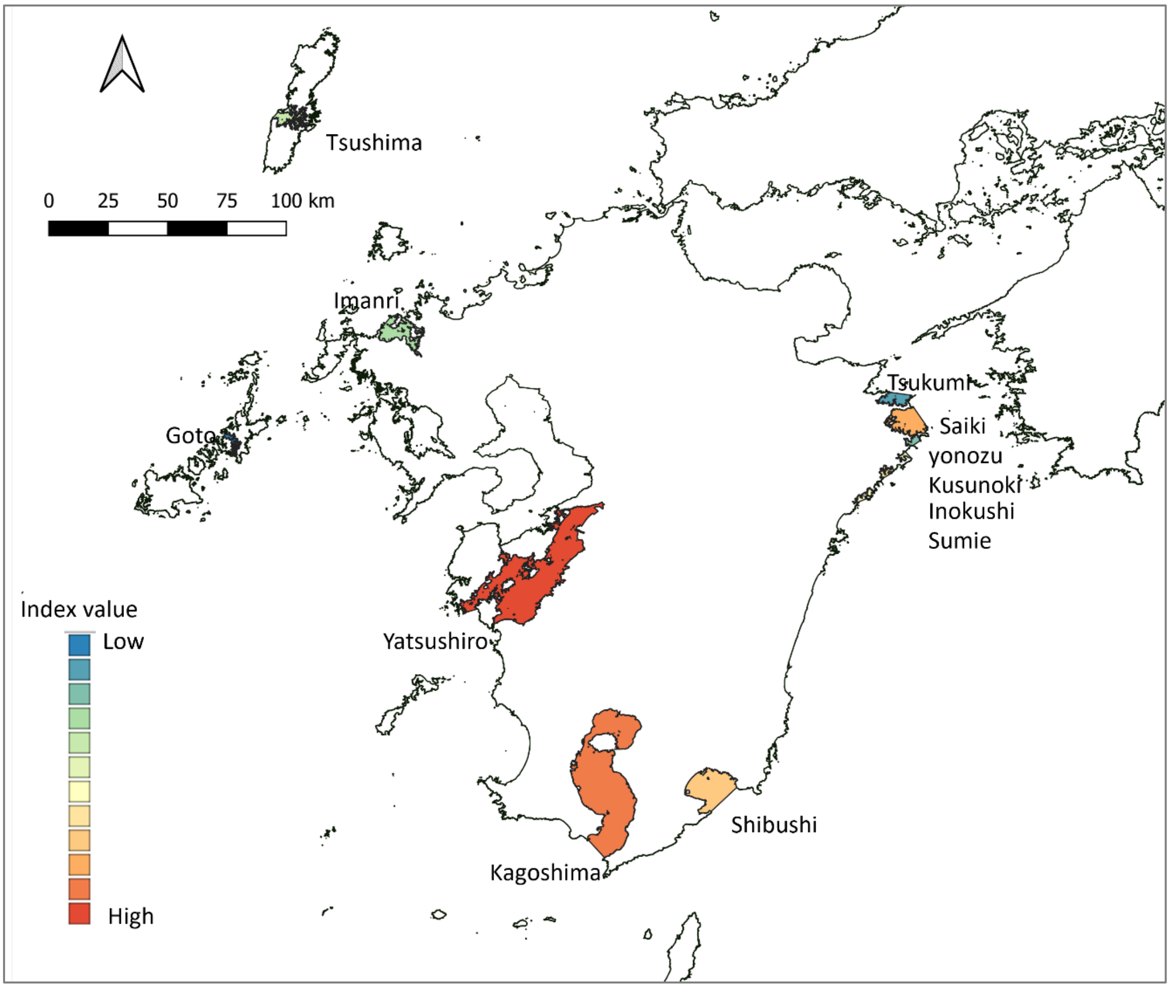


Figure 10. Fish production distribution of 12 main cultured bay areas in Kyushu. Areas with higher value of I_3 mean lower sustainability for marine aquaculture.

The annual aquaculture production in Yatsushiro is the largest at 35,861 tons, and the annual emissions of TN and TP from the farm are about 5972 tons and 868.9 tons, respectively. Yatsushiro has the largest watershed area of about 3000 km^2, and the annual inflow of TN and TP from land is about 4444 tons and 300 tons, respectively. The highest index value of Yatsushiro indicates that the unit water body receives the highest proportion of nutrient load. Moreover, according to the Japanese government's evaluation of the closure of the bays, the closure degree of Yatsushiro is very high at 32.49, and the sea area with closure degree greater than 1 is considered to need to implement sewage discharge regulations by the government.

Kagoshima has the second-highest index value, with a closure degree of 6.26. The annual cultured fish production in Kagoshima is 19,612 tons, and the annual emissions of TN and TP from the farm are about 3139 tons and 470.8 tons, respectively. The watershed area is about 2000 km^2, and the annual inflow of TN and TP from land is about 2655 tons and 220 tons, respectively. Moreover, the average distance from the farms to the mouth of the bay of Kagoshima is the largest, about 43 km.

Saiki and Shibushi rank third and fourth in index values, respectively, where TN and TP emissions from land are smaller than emissions from farms. The possible reason is that these two bays have first-class rivers flowing into them, and the bay areas are not large, 170 km^2 and 330 km^2, respectively, so the unit water body receives more nutrient load from land inflow.

Based on the analysis, Yatsushiro bay shows the most serious environmental problem, where both the nutrient loading and assessment index show the highest value, and red tide problems are frequently reported. Although the fish farming can be continued, the degradation of the surrounding environment does not ensure the sustainable development of aquaculture. Due to the dataset currently obtained, it is difficult to present a threshold value for the index. In the future, more parameters (current velocity, closure degree, etc.) will be considered, and the study area will be enlarged to all cultured bays in Japan. During the improvement of the index and larger amount of the datasets, we are aiming to provide a threshold value of the assessment index.

4. Conclusions

To evaluate the sustainability of inshore marine aquaculture, this study proposes an assessment index to analyze the factors that may have an impact on the environmental capacity of the aquaculture area. The results show that the location of the fish farm may be a key factor impacting of the water environment from aquaculture, in addition to the large amount of nutrient load discharged into the water body from fish farms and land inflow. The location of the fish farms had an effect on the residence time of nutrients within the bay. In addition to farm location, current velocity also affected residence time and water exchange rate within a bay. In the future, more sophisticated models with hydrodynamics parameters will be added to improve the assessment index. In addition, among the 12 major aquaculture bays in the Kyushu region, eight of them had more nutrient loads from farms than land inflow. Therefore, in the planning of marine aquaculture, the amount of aquaculture, the location of the farm, the inflow of nutrient load on the land, and the geographical characteristics of the bay should be considered to measure the sustainability of the aquaculture in the sea area.

Since only 10 bays are analyzed in this research, the dataset is currently not big enough, the correlation coefficient is easier to be affected by any point. Additionally, it is difficult to provide a threshold value for the index due to current dataset scale. In the future, the study area will be enlarged to whole cultured bays in Japan. More datasets will be included to analyze the performance of the assessment index.

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References

1. Merino, G.; Barange, M.; Blanchard, J.L.; Harle, J.; Holmes, R.; Allen, I.; Rodwell, L.D. Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate? *Glob. Environ. Change* **2012**, *22*, 795–806. [CrossRef]
2. Gowen, R.J.; Bradbury, N.B. The ecological impact of salmonid farming in coastal waters: A review. *Oceanogr. Mar. Biol.* **1987**, *25*, 563–575.

3. Gowen, R.J. Aquaculture and the environment. In *Aquaculture and the Environment: Reviews of the International Conference Aquaculture Europe '91, Dublin, Ireland, 10–12 June 1991*; Special Publication; European Aquaculture Society: Ostend, Belgium, 1992.
4. Ervik, A.; Hansen, P.K.; Aure, J.; Stigebrandt, A.; Johannessen, P.; Jahnsen, T. Regulating the local environmental impact of intensive marine fish farming I. The concept of the MOM system (Modelling-Ongrowing fish farms-Monitoring). *Aquaculture* **1997**, *158*, 85–94. [CrossRef]
5. Campbell, B.; Pauly, D. Mariculture: A global analysis of production trends since 1950. *Mar. Policy* **2013**, *39*, 94–100. [CrossRef]
6. Stigebrandt, A.; Aure, J.; Ervik, A.; Hansen, P.K. Regulating the local environmental impact of intensive marine fish farming: III. A model for estimation of the holding capacity in the Modelling–Ongrowing fish farm–Monitoring system. *Aquaculture* **2004**, *234*, 239–261. [CrossRef]
7. Yokoyama, H.; Inoue, M.; Abo, K. Estimation of the assimilative capacity of fish-farm environments based on the current velocity measured by plaster balls. *Aquaculture* **2004**, *240*, 233–247. [CrossRef]
8. Kitazawa, D.; Zhou, J.; Park, S.; Zhang, J.; Dong, S.; Li, Q.; Yoshida, T. Study on numerical analysis of environmental capacity in aquaculture area. In Proceedings of the Annual Meeting of the Japanese Society of Fisheries Engineering, Fukui, Japan, 8–11 September 2019; pp. 99–100. (In Japanese)
9. Zhang, J.; Kitazawa, D. Assessing the bio-mitigation effect of integrated multi-trophic aquaculture on marine environment by a numerical approach. *Mar. Pollut. Bull.* **2016**, *110*, 484–492. [CrossRef] [PubMed]
10. Closed Sea Area Information. Available online: https://www.emecs.or.jp/info (accessed on 20 May 2019).
11. Yokoyama, H.; Nishimura, A.; Inoue, M. Impact of aquaculture activity and topography on macroventus communities and sediments at fish farms along the Kumano-nada coast. *Bull. Jpn. Soc. Fish. Oceanogr.* **2002**, *66*, 113–141.
12. Sklar, F.H.; Joan, A.B. Coastal environmental impacts brought about by alterations to freshwater flow in the Gulf of Mexico. *Environ. Manag.* **1998**, *22*, 547–562. [CrossRef] [PubMed]
13. Ayache, F. Environmental characteristics, landscape history and pressures on three coastal lagoons in the southern Mediterranean region: Merja Zerga (Morocco), Ghar El Melh (Tunisia) and Lake Manzala (Egypt). *Hydrobiologia* **2009**, *622*, 15–43. [CrossRef]
14. Wu, P. Effects of nutrient on algae biomass during summer and winter in inflow rivers of Taihu Basin, China. *Water Environ. Res.* **2016**, *88*, 665–672. [CrossRef] [PubMed]
15. Statistics of Japan. Sea Surface Fishery Production Statistics Survey. Available online: https://www.e-stat.go.jp/stat-search/files?page=1&layout=datalist&toukei=00500216&tstat=000001015174&cycle=7&year=20180&month=0&tclass1=000001015175&tclass2=000001136043 (accessed on 10 March 2019).
16. Fishieries Agency. Red Tide in Kyushu Area. Available online: https://www.jfa.maff.go.jp/kyusyu/sigen/akashio_kyusyu.html (accessed on 14 May 2020).
17. Gao, H.; Wang, Y.; Dong, S.; Kitazawa, D. Sustainability assessment based on the aquaculture intensity index (aii) approach: A case study in oita prefecture japan. In Proceedings of the 9th East Asian Workshop for Marine Environment and Energy, Osaka, Japan, 27–29 October 2019; pp. 1–8.
18. Gao, H.; Xu, G.; Zhou, J.; Dong, S.; Li, Q.; Yoshida, T.; Kitazawa, D. Sustainability Assessment of Marine Aquaculture Based on A Simple Index in Kyushu, Japan. In Proceedings of the Global Oceans 2020: Singapore–US Gulf Coast, 5–30 October 2020; pp. 1–8.
19. Gentry, R.R.; Froehlich, H.E.; Grimm, D.; Kareiva, P.; Parke, M.; Rust, M.; Halpern, B.S. Mapping the global potential for marine aquaculture. *Nat. Ecol. Evol.* **2017**, *1*, 1317–1324. [CrossRef]
20. Aquaculture Farm Database. Available online: http://www.yousyokugyojyou.net/index2a.html (accessed on 20 September 2019).
21. MDA Situational Indication Linkage. Available online: https://www.msil.go.jp/msil/Htm/TopWindow.html (accessed on 3 September 2019).
22. Cromey, C.J.; Nickell, T.D.; Black, K.D. Depomod–modelling the deposition and biological effects of waste solids from marine cage farms. *Aquaculture* **2002**, *214*, 211–239. [CrossRef]
23. Bureau, D.P.; Gunther, S.J.; Cho, C.Y. Chemical composition and preliminary theoretical estimates of waste outputs of rainbow trout reared in commercial cage culture operations in Ontario. *N. Am. J. Aquac.* **2003**, *65*, 33–38. [CrossRef]
24. Reid, G.K.; Liutkus, M.; Robinson, S.M.C.; Chopin, T.R.; Blair, T.; Lander, T.; Moccia, R.D. A review of the biophysical properties of salmonid faeces: Implications for aquaculture waste dispersal models and integrated multi-trophic aquaculture. *Aquac. Res.* **2009**, *40*, 257–273. [CrossRef]
25. Wang, X.; Olsen, L.M.; Reitan, K.I.; Olsen, Y. Discharge of nutrient wastes from salmon farms: Environmental effects, and potential for integrated multi-trophic aquaculture. *Aquac. Environ. Interact.* **2012**, *2*, 267–283. [CrossRef]
26. Takashi, U. Organic matter load and chemical properties of seafloor sediments associated with fish farming. *Res. J. Food Agric.* **2008**, *31*, 24–28.
27. Buschmann, A.; Costa-Pierce, B.A.; Cross, S.; Iriarte, J.L.; Olsen, Y.; Reid, G. Nutrient Impacts of Farmed Atlantic Salmon (Salmo Salar) on Pelagic Ecosystems and Implications for Carrying Capacity. 2007. Available online: https://www.researchgate.net/publication/282295533_NUTRIENT_IMPACTS_OF_FARMED_ATLANTIC_SALMON_Salmo_salar_ON_PELAGIC_ECOSYSTEMS_AND_IMPLICATIONS_FOR_CARRYING_CAPACITY (accessed on 15 April 2021).
28. Lesack, L.F.; Hecky, R.E.; Melack, J.M. Transport of carbon, nitrogen, phosphorus, and major solutes in the Gambia River, West Africa 1. *Limnol. Oceanogr.* **1984**, *29*, 816–830. [CrossRef]
29. Matsumura, T.; Ishimaru, T. Freshwater inflow to Tokyo Bay and nitrogen/phosphorus inflow load (1997, 1998). *Sea Stud.* **2004**, *13*, 25–36.

30. Comprehensive Plan Survey of Sewerage Maintenance by Basin. Available online: https://www.mlit.go.jp/mizukokudo/sewerage/mizukokudo_sewerage_tk_000383.html (accessed on 10 April 2021).
31. Ukita, M.; Nakanishi, H.; Sekine, M. The pollutant load factor of household wastewater in Japan. *Water Sci. Technol.* **1986**, *18*, 157–167. [CrossRef]
32. Kodani, E. Estimating total nitrogen (TN) emission load in the Shimanto River basin by the basic unit method using GIS. *For. Appl. Res.* **2003**, *12*, 99–107.
33. Kunimatsu, T.; Muraoka, H. *Model Analysis of River Pollution*; Gihodo Shuppan: Tokyo, Japan, 1989. (In Japanese)
34. Takahashi, H.; Yoshikawa, S.; Takano, H.; Sasada, Y.; Ninomiya, S. Estimating the inflow load from the Okayama/Kagawa basin to the Seto Inland Sea in consideration of basin characteristics. *Limnol. Mag.* **2010**, *71*, 269–284.
35. Yuasa, T.; Matsumaru, R.; Aramaki, T.; Manago, G.; Shibata, K.; Aye, S.T.; Suzuki, A. Applying Pollutant Load Factor Method for Estimation of Pollution Load and Evaluation of Pollutant Factors in Inle Lake, Myanmar. *J. Jpn. Soc. Civ. Eng.* **2020**, *76*, I_9–I_18. [CrossRef]
36. *Research on Advanced Treatment of Simultaneous Removal of Nitrogen and Phosphorus in Sewerage*; Annual Report of JIWET; Japan Sewerage New Technology Organization: Tokyo, Japan, 2001.
37. Statistics Bureau of Japan. 2015 Census. Available online: https://www.stat.go.jp/data/kokusei/2015/kekka.html (accessed on 15 April 2021).
38. Ministry of the Environment Gorvenment of Japan. Sewage Treatment Population Diffusion Status at the End of 2018. Available online: https://www.env.go.jp/press/107120.html (accessed on 15 April 2021).
39. Ministry of Agriculture, Forestry and Fisheries. Livestock Statistics Survey. Available online: https://www.maff.go.jp/j/tokei/kouhyou/tikusan/index.html (accessed on 20 May 2021).
40. Ministry of Economy, Trade and Industry. Industrial Statistics Survey. Available online: https://www.meti.go.jp/statistics/tyo/kougyo/ (accessed on 25 May 2021).
41. Ministry of Land, Infrastructure, Transport and Tourism. Land Use Tertiary Mesh Data. Available online: https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-L03-a.html (accessed on 25 June 2021).
42. Ministry of Land, Infrastructure, Transport and Tourism. Watershed Boundary Data. Available online: https://nlftp.mlit.go.jp/ksj/jpgis/datalist/KsjTmplt-W07.html (accessed on 30 June 2021).
43. Ministry of Land, Infrastructure, Transport and Tourism. Elevation Mesh Data. Available online: https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-G04-a.html (accessed on 27 September 2021).