

Article

Environmental Concerns for Sustainable Mariculture in Coastal Waters of South-Central Vietnam

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Abstract: Mariculture provides an increasing seafood supply to a growing population. It also brings unintended consequences for the environment, resources, and sustainable development. In an attempt to evaluate the impacts of intensive mariculture of lobster in cages, the water quality and sediment quality in three South-Central regions of Vietnam, Xuan Dai Bay, Van Phong Bay, and Cam Ranh Bay, were monitored from April 2019 to May 2020. In each bay, two stations in the farming areas were compared to a non-farming reference station. The result showed no significant differences in the water quality parameters among the stations within each bay and between the bays. However, sediment quality noticeably differed between sites within each bay and between the bays. The accumulation of the observed parameters of sediment in farming areas was higher than in non-farming areas. In the Cam Ranh Bay, the concentration of organic carbon, total nitrogen, and total phosphorus in the sediment in farming areas was approximately 1.4 times higher compared to non-farming areas. Similar results were found in Van Phong Bay and Xuan Dai Bay with different magnitudes. Additionally, the difference in the sulfide concentration in the sediment of Van Phong Bay was notable for its better environmental quality than the other two. The findings indicated that mariculture wastes would accumulate in the sediment, and decompose over time, causing sediment degradation, which may affect the benthic biota in coastal waters.

Keywords: water quality; nutrient concentrations; sediment degradation; lobster culture



Citation: Phu, L.H.; Kim-Hong, P.T.; Chung, T.V.; Binh, T.V.; Dung, L.T.; Ngoc, P.H.; Thu, N.H.; Thu, N.T.T.; Anh, N.T.H.; Nguyen, A.L.; et al. Environmental Concerns for Sustainable Mariculture in Coastal Waters of South-Central Vietnam. *Sustainability* **2022**, *14*, 8126. <https://doi.org/10.3390/su14138126>

Academic Editor: Marianna Cavallo

Received: 23 May 2022

Accepted: 1 July 2022

Published: 3 July 2022

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1. Introduction

Aquaculture plays a vital role in the world's food security as a result of the rapid growth of its production. For the first two decades of the 21st century, aquaculture production increased at an average rate of more than 5% year⁻¹ due to rising food demands [1]. According to FAO [1], the world's fishery production reached 179 million tonnes, in which total aquaculture production accounted for 46%, and contributed to 52% of human demand for fish. In addition, mariculture production accounted for 37.5% of aquaculture production in 2018. Total aquaculture products are forecasted to experience an increase of 53% in aquatic production by 2030 [1]. Aquaculture production accounted for 52% of fish for human demands [1]. Fish consumption per capita rose from 9.0 kg in 1961 to 20.3 kg in 2017, with an average rate of about 1.5% year⁻¹, which is higher than the increase in total meat consumption which grew by 1.1% year⁻¹ [1].

In Vietnam, aquaculture has experienced significant development with an increase in cultured species, spatial regions, and farming systems [2]. In 1995, the total aquatic production was 890.6 thousand tonnes, to which aquaculture contributed 162.1 thousand tonnes, whereas the total aquatic production reached 8497 thousand tonnes in 2020, of which aquaculture accounted for about 54% [3].

Lobster cage culture occurs from Quang Binh to Binh Thuan provinces with major production in Phu Yen and Khanh Hoa. The two provinces are located in South-Central Vietnam with many enclosed bays that are suitable for the development of shellfish, fish and lobster cage farming. The total number of cages in Phu Yen and Khanh Hoa provinces was 185,166 in 2019, accounting for 97.8% of the lobster cages in Vietnam; production reached 2273 tons, accounting for 95% of the country's lobster aquaculture production [3]. Information on the cage culture in Xuan Dai Bay, Van Phong Bay and Cam Ranh Bay is presented in Table 1.

Table 1. Situation of lobster cage farming in some locations of Phu Yen and Khanh Hoa provinces in 2020 (Song Cau Department of Economics, 2020, unpublished report; Khanh Hoa Sub-Department of Fisheries, 2020, unpublished report).

Provinces	Location	Type of Farming	Number of Cages	Products (tonnes)
Phu Yen	Total	Lobster cages	79,073	732
	Xuan Dai Bay	Lobster cages	79,073	732
		Finfish cages	721	65.5
Khánh Hòa	Total	Lobster cages	60,647	1540.4
		Finfish cages	9072	8288.4
	Van Phong Bay	Lobster cages	33,167	-
	Cam Ranh Bay	Lobster cages	34,914	-

However, aquaculture, similarly to many other agricultural sectors, is known to have several negative impacts on the environment and natural resources [4–8], especially in coastal waters [4–8]. These impacts could be chemical accumulations (e.g., heavy metals, antifouling biocides, aquaculture medicinal products, polycyclic aromatic hydrocarbons, and warfare agents by anthropogenic inputs) [9–15], nutrient loads [8,11,12,16,17], organic matter deposited in sediment [11,12,18], and habitat destruction [8,19,20] as well as negative interaction of invasive species with wild fish [21,22]. Aquaculture is also known to cause an increase in eutrophication [23–27] and algal blooms [28–31] in coastal waters, a reduction in dissolved oxygen in seawater [32], and expanded dead zones for coastal waters [33,34]. In addition, the increased culture in coastal waters could overload the environmental carrying capacity [35] and cause outbreaks of diseases [36–38].

Furthermore, mariculture might cause unwanted socio-economic issues in coastal waters. It might lead to changes in the morphology and land(sea)scape in mariculture and adjacent regions that could impact properties, settlements, transport routes and viewpoints, thereby detracting the value of those places [39–42]. Using chemicals such as antibiotics, pesticides, genetically modified organisms, antiparasitic and artificial colorings could indirectly impact on consumers' health due their accumulation in cultured fish [43–45]. In addition, mariculture development could cause competition over natural resources [42,46,47]. Barnaby and Adams [48] noted fishermen had to face the loss of fishing ground due to aquaculture development, which led to resource conflict [49]. Such disease outbreaks, food safety recalls, or natural disasters could lead to boom and bust cycles or collapses of the aquaculture sector [49]. The development of aquaculture also means an increase in debt affecting traditional society [49]. Lobster cage culture farmers using low valued fish as traditional feed [36,50] has led to potential impacts on marine resources. As a result, the lives of local communities, such as fisherman and fishing farmers may be affected directly or indirectly by environmental degradation, chemical use in aquaculture and resource depletion.

The above arguments led us to conduct the present study, which aimed to elucidate the influence of marine cage culture on environmental quality. The environmental concerns in the South-Central region of Vietnam were also explored.

2. Materials and Methods

2.1. Study Areas

This study investigated the following three coastal waters in South-Central Vietnam: Xuan Dai Bay, Van Phong Bay, and Cam Ranh Bay (Figure 1). Xuan Dai Bay is a 9000 ha semi-enclosed bay in Phu Yen province reaching its greatest depth at 12 m. Van Phong Bay is a 150,000 ha semi-opened bay in the northern part of Khanh Hoa province with a maximum depth, at the Co Co area, of over 34 m. Cam Ranh Bay is a body of enclosed water in the southern part of Khanh Hoa province. The bay has an area of 11,900 hectares and is up to approximately 16 m in depth.

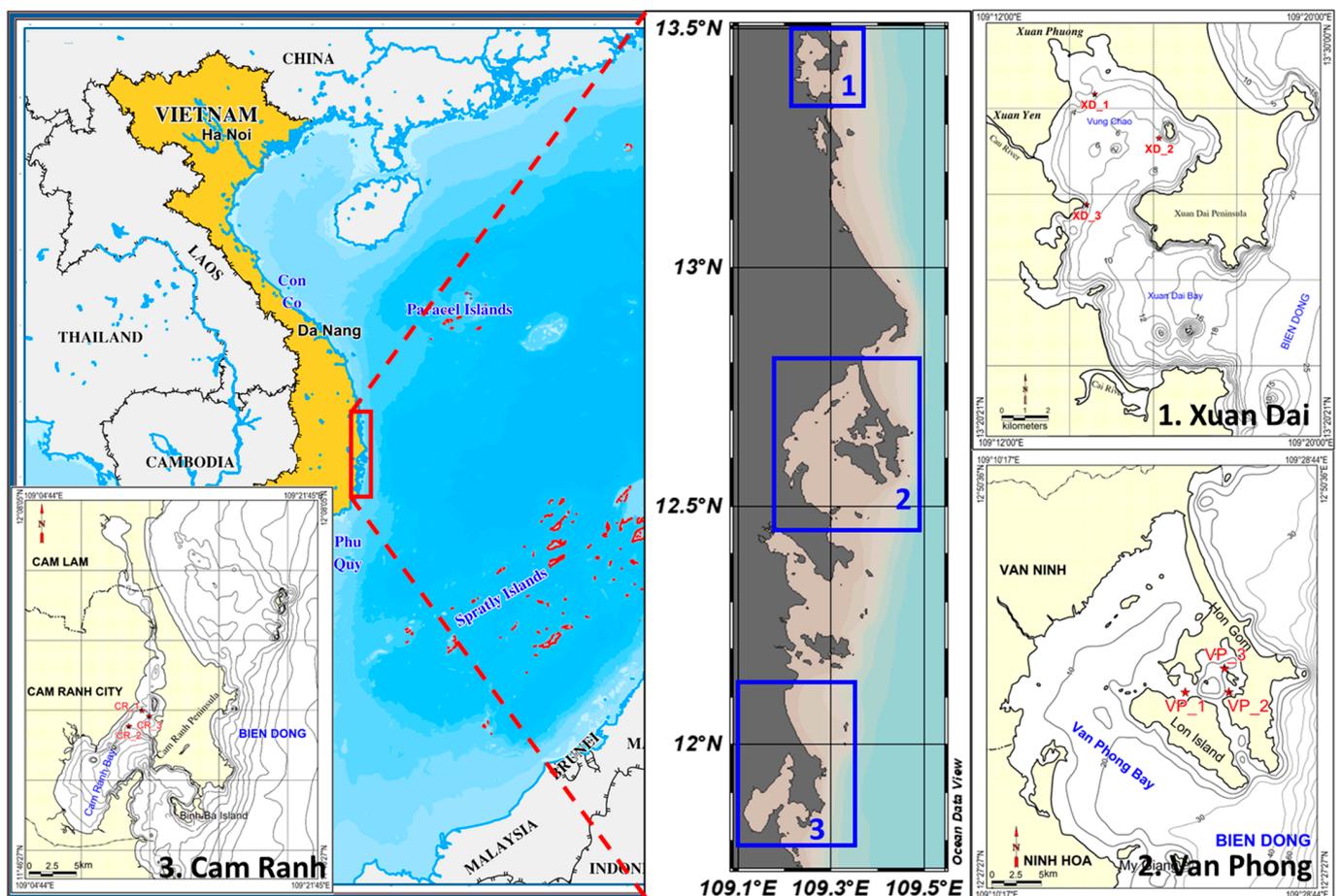


Figure 1. Coastal waters sampled in South-Central Vietnam (★ in red denotes the study station). 1. Xuan Dai Bay (XD) presented the regions of lobster cage culture for 20 years; 2. Van Phong Bay (VP) for 10 years; 3. Cam Ranh Bay (CR) in recent years. For each region, two stations (1 and 2) were located inside lobster cage culture areas and one reference (non-farming) station (3) was located outside of culture areas.

2.2. Sampling Collection

Environmental data of seawater and sediment in the mariculture regions were surveyed at nine stations (three stations per region, coded XD for Xuan Dai Bay, VP for Van Phong Bay, and CR for Cam Ranh Bay) by five visits in the dry season (four visits at CR) and two visits in the rainy season from May 2019 to May 2020 (Table 2 and Figure 1). Two stations (1 and 2) were located inside of the lobster cage culture areas and one reference

station was from a non-farming area (3). At each sampling station, seawater temperature, pH, salinity, dissolved oxygen concentration (DO), and the redox potential (Eh) of sediments were measured by the YSI ProDSS meter (USA) and HANNA pH meter 8424 (USA). Seawater samples were collected at a water depth of -1 m with a 5-L Niskin bottle, whereas sediment samples were collected on the bottom substrate surface using a grab sampler of 0.25 m². Samples were kept in the dark and on ice until transferred to the laboratory during daytime.

Table 2. Times of sampling in each study bay.

Regions	District	Station Code in Figure 1	Dry Seasons	Rainy Seasons
Xuan Dai Bay	Song Cau Town	XD_#	April, June, August 2019 March & May 2020	November 2019 & Januray 2020
Van Phong Bay	Van Ninh District	VP_#	April, June, August 2019 March & May 2020	November 2019 & Januray 2020
Cam Ranh Bay	Cam Ranh City	CR_#	April, June, August 2019 March 2020	November 2019 & Januray 2020

2.3. Sample Analyses

At the laboratory in the Institute of Oceanography, Vietnam Academy of Science and Technology, the biological oxygen demand (BOD₅) was analyzed immediately, whereas samples for other environmental factors were stored at -20 °C until analysis within a week. Seawater and sediment samples were analyzed in the laboratory using procedures described in the *Standard Methods for the Examination of Water and WasteWater* 23rd edition [51]. Water samples were measured for BOD₅ (method 5210-B), Nitrite (method 4500-NO₂⁻), Nitrate (method 4500-NO₃⁻), organic nitrogen Kjeldahl (method 4500-N_{org}), total nitrogen (TN) (sum of organic nitrogen and inorganic nitrogen) and total phosphorus (method 4500-P).

For sediment samples, organic carbon was measured using Walkley–Black titration. Sediment samples were treated with a mixture of potassium dichromate solution (K₂Cr₂O₇) and concentrated sulfuric acid. Then, the excess dichromate was back-titrated with the ferrous ammonium sulfate (Fe(NH₄)₂(SO₄)₂·6H₂O) solution [51]. Total nitrogen was measured using the Kjeldahl method, in which ammonium, digested from all of the nitrogen types, was determined using the titration method with a NaOH solution [51]. Total phosphorus was measured by sulfuric-nitric acid digestion and orthophosphate was measured by the ascorbic method [51]. Free sulfide was identified using a colorimetric procedure [51]. Sulfide was released using hydrochloric acid and trapped with a sodium hydroxide solution. The concentration of sulfide was then determined spectrophotometrically as methylene blue.

2.4. Data Analyses

Data were analyzed using SPSS version 22 with Bonferroni correction and a two-tail Student-T test. Data were also compared with the environmental standard for aquaculture in the National technical regulation on marine water quality (QCVN 10-MT:2015/BTNMT) and the National technical regulation on sediment quality (QCVN 43:2017/BTNMT). Nevertheless, the sediment environmental factors in this study were not included in the QCVN 43:2017/BTNMT. Thus, the sediment factors were compared to other standards of international countries, such as the USA [52] and Norway [53].

3. Results

3.1. Water Environment

For water quality, a variation of the observed parameters (Table 3) showed that in general, most of the values of environmental parameters met the requirements of QCVN 10-MT:2015/BTNMT of Vietnam. However, the lowest DO values were below the standard in July 2019 (Xuan Dai Bay and Van Phong Bay) and in March 2020 (Cam Ranh Bay), but these were instantaneous values, and the average seasonal value in each region met the minimum requirements of the environmental standards of Vietnam.

Table 3. Mean and range of environmental water factors in each study bay for different seasons.

Factor		Rainy Season			Dry Season			QCVN 10:2015
		Xuan Dai	Van Phong	Cam Ranh	Xuan Dai	Van Phong	Cam Ranh	
pH	Minimum	8.02 _a	8.01 _a	8.01 _a	7.80 _a	7.78 _a	7.71 _a	6.5–8.5
	Maximum	8.09 _a	8.09 _a	8.05 _a	8.14 _a	8.31 _a	8.32 _a	
	Mean	8.05 _a	8.04 _a	8.02 _a	8.01 _a	8.10 _a	8.07 _a	
	SE	0.01 _a	0.01 _a	0.01 _a	0.03 _a	0.05 _a	0.07 _a	
Temperature (°C)	Minimum	24.3 _{a,b}	24.4 _a	24.1 _b	27.0 _a	28.0 _a	28.6 _a	
	Maximum	24.7 _{a,b}	24.9 _a	24.5 _b	31.3 _a	30.6 _a	31.6 _a	
	Mean	24.4 _{a,b}	24.7 _a	24.2 _b	29.4 _a	29.3 _a	30.0 _a	
	SE	0.1 _{a,b}	0.1 _a	0.1 _b	0.4 _a	0.2 _a	0.2 _a	
Salinity (‰)	Minimum	30.90 _a	32.20 _b	32.10 _b	30.64 _a	32.35 _a	30.90 _a	
	Maximum	31.80 _a	32.50 _b	32.60 _b	34.30 _a	33.50 _a	33.70 _a	
	Mean	31.43 _a	32.30 _b	32.30 _b	32.61 _a	32.81 _a	32.65 _a	
	SE	0.15 _a	0.05 _b	0.09 _b	0.29 _a	0.12 _a	0.29 _a	
DO (mg O ₂ /L)	Minimum	5.76 _a	6.56 _a	5.06 _b	3.94 _a	4.65 _a	4.16 _a	≥5
	Maximum	6.99 _a	6.93 _a	5.80 _b	7.11 _a	7.12 _a	7.45 _a	
	Mean	6.52 _a	6.81 _a	5.53 _b	5.61 _a	6.27 _a	5.61 _a	
	SE	0.21 _a	0.05 _a	0.14 _b	0.30 _a	0.19 _a	0.29 _a	
BOD ₅ (mg O ₂ /L)	Minimum	0.84 _a	0.67 _a	0.45 _a	0.59 _a	0.97 _a	0.27 _a	
	Maximum	3.06 _a	2.61 _a	2.10 _a	3.28 _a	5.42 _a	3.11 _a	
	Mean	1.94 _a	1.59 _a	1.24 _a	2.29 _a	2.77 _a	1.93 _a	
	SE	0.38 _a	0.35 _a	0.29 _a	0.21 _a	0.31 _a	0.34 _a	
NO ₂ (mg N/m ³)	Minimum	3.9 _a	4.9 _a	3.6 _a	2.7 _a	1.9 _a	1.8 _a	
	Maximum	5.7 _a	6.1 _a	8.3 _a	8.8 _a	6.9 _a	12.7 _a	
	Mean	4.8 _a	5.5 _a	5.5 _a	5.0 _a	3.7 _a	6.4 _a	
	SE	0.3 _a	0.2 _a	0.6 _a	0.5 _a	0.5 _a	1.1 _a	
NO ₃ (mg N/m ³)	Minimum	65.0 _a	62.0 _b	79.0 _a	42.0 _a	43.0 _a	39.0 _a	
	Maximum	126.0 _a	85.0 _b	125.0 _a	85.0 _a	92.0 _a	81.0 _a	
	Mean	106.0 _a	75.3 _b	106.7 _a	65.2 _a	67.1 _a	64.6 _a	
	SE	8.6 _a	3.1 _b	7.6 _a	4.3 _a	4.4 _a	4.5 _a	
Total nitrogen (mg N/m ³)	Minimum	624.9 _a	618.7 _a	663.7 _a	580.5 _a	651.5 _a	596.3 _a	
	Maximum	710.3 _a	726.5 _a	790.6 _a	985.2 _a	925.7 _a	956.8 _a	
	Mean	659.0 _a	672.3 _a	720.2 _a	721.7 _a	808.3 _a	738.6 _a	
	SE	14.5 _a	20.3 _a	16.9 _a	33.9 _a	19.7 _a	29.7 _a	
Total phosphorus (mg P/m ³)	Minimum	57.9 _a	42.4 _b	55.9 _a	45.6 _a	43.8 _a	45.7 _a	≤200
	Maximum	77.1 _a	69.2 _b	85.2 _a	80.2 _a	74.5 _a	89.9 _a	
	Mean	68.3 _a	54.4 _b	71.1 _a	59.6 _a	58.6 _a	65.6 _a	
	SE	2.7 _a	3.7 _b	4.5 _a	2.6 _a	2.3 _a	4.4 _a	

Note: Values in the same row and sub-table not sharing the same subscript were significantly different at $p < 0.05$ in the two-sided test of equality for column means. Tests assumed equal variances. Tests were adjusted for all pairwise comparisons within a row of each innermost sub-table using Bonferroni correction. SE: Standard Error of Mean.

Biological oxygen demand (BOD₅) values measured within the farming areas varied from 0.32 to 5.42 mg/L, whereas those values at the reference stations ranged from 0.27 to

4.35 mg/L (Table 3 and Figure 2). Variations of BOD₅ values in the farming areas showed a similar pattern to the reference waters and there were no significant differences within and outside the farming areas, but they fluctuated during the studied period. The highest BOD₅ value in the farming areas (5.42 mg/L) and reference station (4.35 mg/L) occurred in March 2020 in Van Phong Bay. Furthermore, the lowest BOD₅ values were found in March 2020 at Cam Ranh Bay (0.27 mg/L at reference stations, 0.32 mg/L at farming areas).

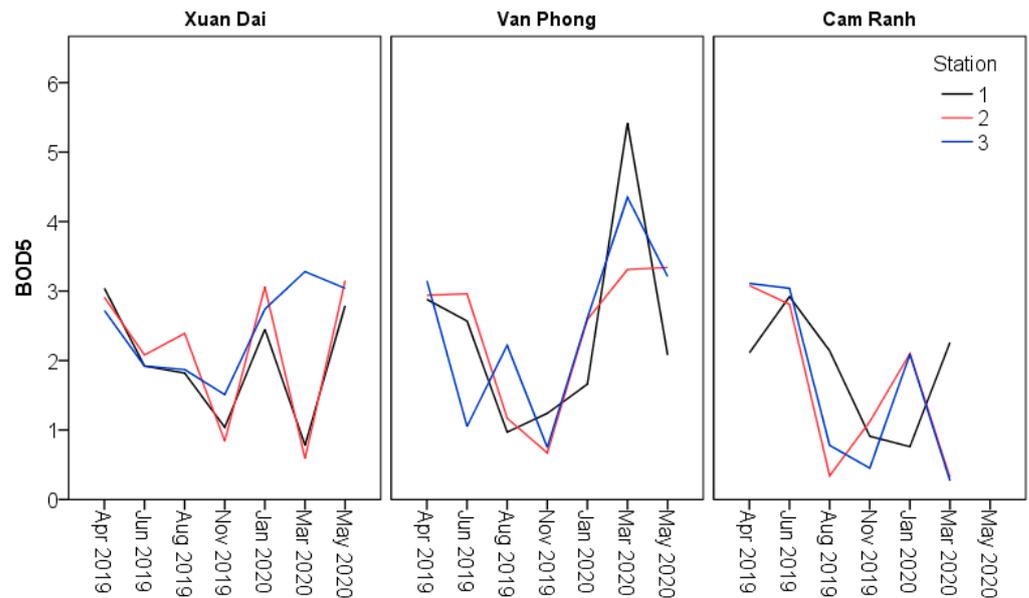


Figure 2. Variation of BOD₅ (mg O₂ L⁻¹) in seawater in each studied bay. Stations 1 and 2 within farming areas, and Station 3 as reference.

Variations in nitrate concentrations within farming areas were similar to the pattern in the reference stations (Figure 3). Nitrate concentrations in Cam Ranh and Xuan Dai increased from a minimum in June 2019 to a peak in November. Differences in nitrate concentrations between farming areas and reference stations were insignificant (Figure 3).

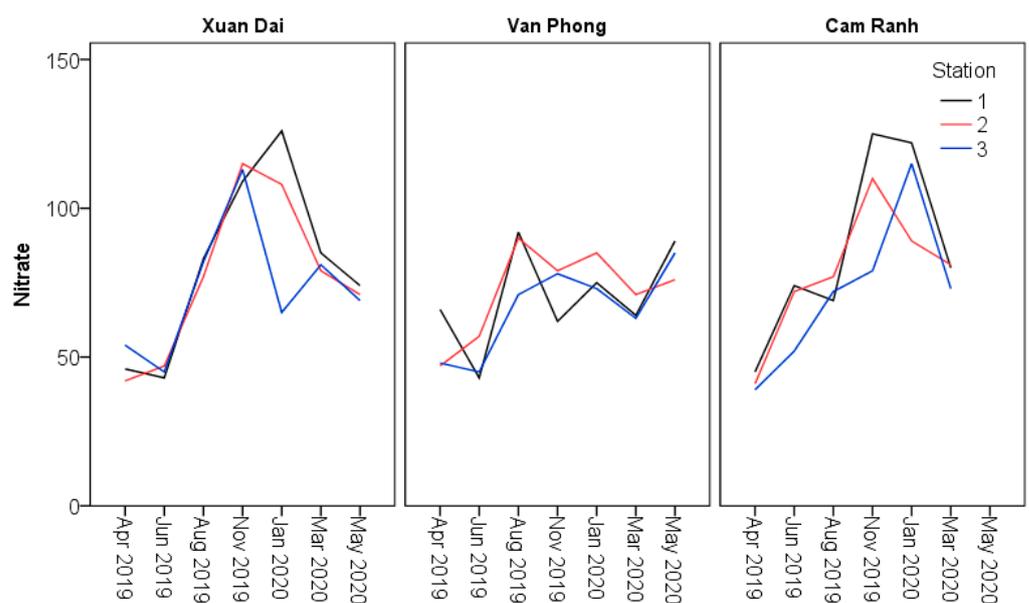


Figure 3. Variation of nitrate (mg N m⁻³) in seawater in each studied bay. Stations 1 and 2 within farming areas, and Station 3 as reference.

Total nitrogen (TN) concentrations were in the range of 596.3–985.2 mg N m⁻³ in farming areas and 580.5–945.6 mg N m⁻³ in the reference stations. The nitrate concentrations in Xuan Dai Bay and Cam Ranh Bay declined over the study period, whereas in Van Phong Bay the concentration declined to the lowest values in Nov 2019 and then increased (Figure 4). The total phosphorus (TP) concentrations in the farming areas and reference stations varied from 42.4 to 89.9 mg P m⁻³ and from 47.8 to 80.5 mg P m⁻³, respectively. TN and TP concentrations in the farming areas and reference stations were not significantly different from each other (Figure 5).

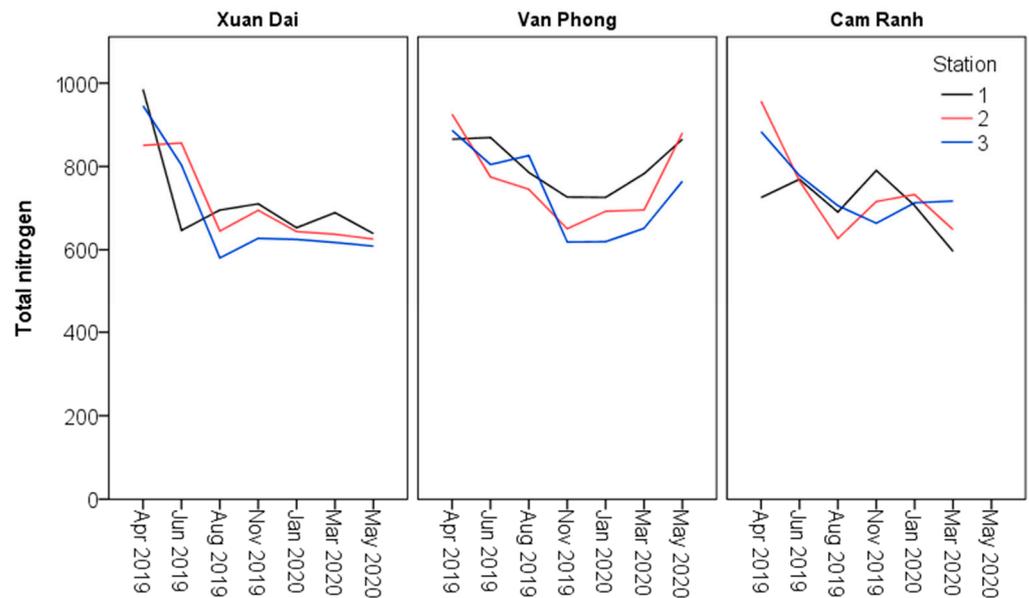


Figure 4. Variation of nitrate (mg N m⁻³) in seawater in each studied bay. Stations 1 and 2 within farming areas, and Station 3 as reference.

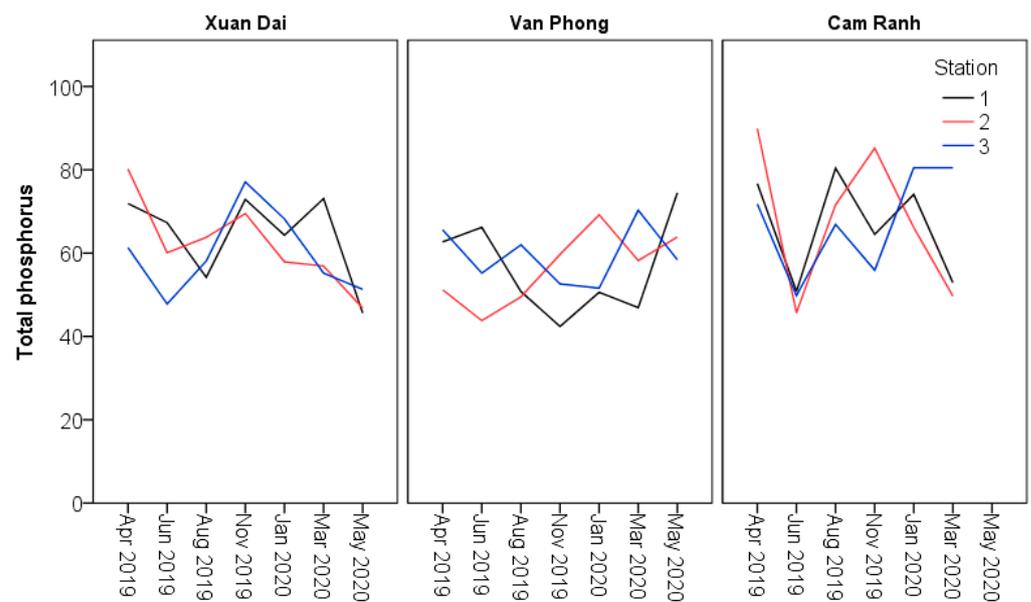


Figure 5. Variation of phosphorus (mg P m⁻³) in seawater in each studied bay. Stations 1 and 2 within farming areas, and Station 3 as reference.

3.2. Sediment Environment

For sediment quality, there were only significant changes in sulfide concentrations between Van Phong Bay with Xuan Dai Bay and Cam Ranh Bay, whereas the changes had a significant variation seasonally (Table 4).

Table 4. Mean and range of sediment environmental factors in each study bay for different seasons.

Factor		Rainy season			Dry season			Sediment Standards
		Xuan Dai	Van Phong	Cam Ranh	Xuan Dai	Van Phong	Cam Ranh	
Eh mV	Minimum	−53.6 _a	−59.3 _a	−58.2 _a	−61.6 _a	−66.3 _a	−51.2 _a	
	Maximum	−38.3 _a	−35.0 _a	−35.0 _a	−26.4 _a	−28.0 _a	−17.6 _a	
	Mean	−47.2 _a	−49.5 _a	−47.6 _a	−46.0 _a	−41.9 _a	−37.8 _a	
	SE	2.7 _a	3.7 _a	3.3 _a	2.9 _a	3.2 _a	3.2 _a	
Sulfide mg S kg ^{−1}	Minimum	18.204 _a	0.274 _b	19.834 _a	7.396 _a	0.149 _b	5.085 _a	≤1500 μM
	Maximum	53.898 _a	3.888 _b	78.031 _a	50.115 _a	3.680 _b	53.559 _a	[52]
	Mean	36.546 _a	1.358 _b	48.214 _a	30.264 _a	1.002 _b	24.638 _a	(≤ 48.097
	SE	5.111 _a	0.644 _b	11.679 _a	3.072 _a	0.268 _b	5.305 _a	mg S kg ^{−1})
Organic Carbon %	Minimum	0.66 _a	0.96 _a	0.94 _a	0.76 _a	0.96 _a	0.88 _a	≤20 mg/g
	Maximum	1.41 _a	1.78 _a	2.21 _a	1.95 _a	2.11 _a	1.85 _a	[53]
	Mean	1.10 _a	1.37 _a	1.37 _a	1.44 _a	1.40 _a	1.29 _a	(≤ 2%)
	SE	0.11 _a	0.12 _a	0.20 _a	0.09 _a	0.07 _a	0.10 _a	
Total Phos- phorus mg P kg ^{−1}	Minimum	197.2 _a	225.4 _a	265.7 _a	165.8 _a	132.0 _a	128.8 _a	
	Maximum	350.7 _a	427.2 _a	412.5 _a	498.2 _a	395.8 _a	446.9 _a	
	Mean	271.9 _a	325.7 _a	317.6 _a	332.4 _a	286.6 _a	274.8 _a	
	SE	26.0 _a	31.4 _a	23.2 _a	23.6 _a	21.6 _a	26.8 _a	
Total Nitrogen mg N kg ^{−1}	Minimum	374.60 _a	552.23 _a	482.60 _a	356.41 _a	281.82 _a	246.40 _a	
	Maximum	648.80 _a	836.24 _a	838.38 _a	894.60 _a	782.70 _a	786.30 _a	
	Mean	500.89 _a	644.86 _a	605.48 _a	622.09 _a	570.60 _a	522.74 _a	
	SE	48.98 _a	41.13 _a	55.80 _a	36.52 _a	37.68 _a	46.12 _a	

Note: Values in the same row and sub-table not sharing the same subscript were significantly different at $p < 0.05$ in the two-sided test of equality for column means. Tests were adjusted for all pairwise comparisons within a row of each innermost sub-table using Bonferroni correction. SE: Standard Error of Mean.

The redox potential (Eh) showed the sediments of the studied areas in an anoxic condition. The sulfide concentrations in Van Phong Bay were significantly lower than in Cam Ranh Bay and Xuan Dai Bay ($p < 0.05$). Those values fluctuated strongly within a studied area (Figure 6). The ranges were 0.15–3.89 mg S kg^{−1} in Van Phong Bay; 5.08–78.03 mg S kg^{−1} in Cam Ranh Bay; and 7.40–53.90 mg S kg^{−1} in Xuan Dai Bay. According to the results of the two-tail Student-T test, sulfide concentrations of farming areas at Van Phong and Xuan Dai Bays were significantly higher than the corresponding reference stations ($p < 0.05$).

Organic carbon (Org C) contents in sediment were similar among the areas studied. These values varied in the range of 0.96–2.11% in Van Phong Bay; 0.88–2.21% in Cam Ranh Bay; and 0.66–1.95% in Xuan Dai Bay (Figure 7). The results showed that all Org C contents in the sediment of the areas studied were lower than 10% (the threshold level of Org C contents for the risks of reduced species richness [54]).

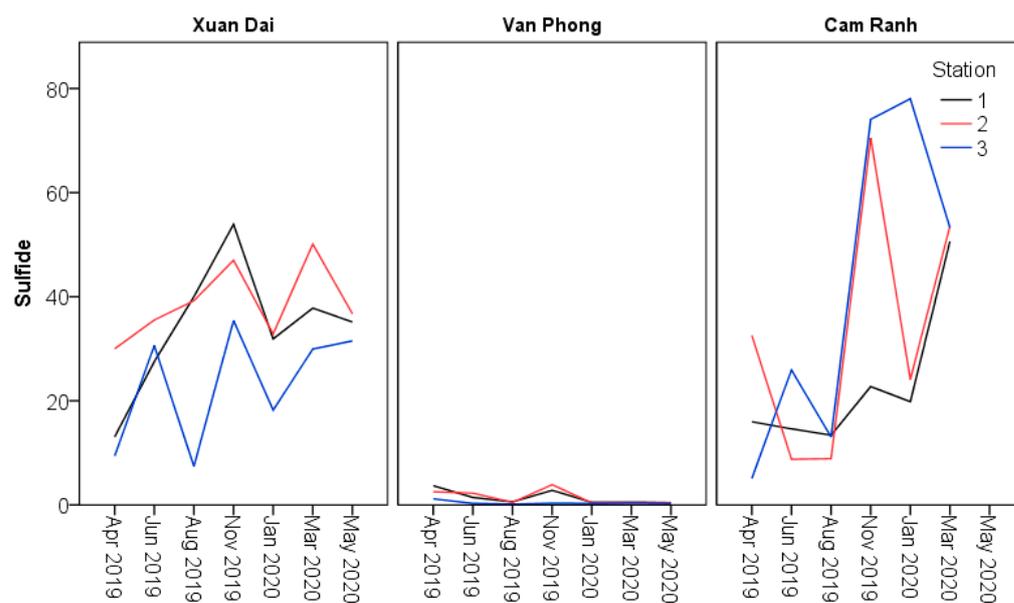


Figure 6. Variation of sulfide (mg S kg^{-1}) in sediment in each studied bay. Stations 1 and 2 within farming areas, and Station 3 as reference one.

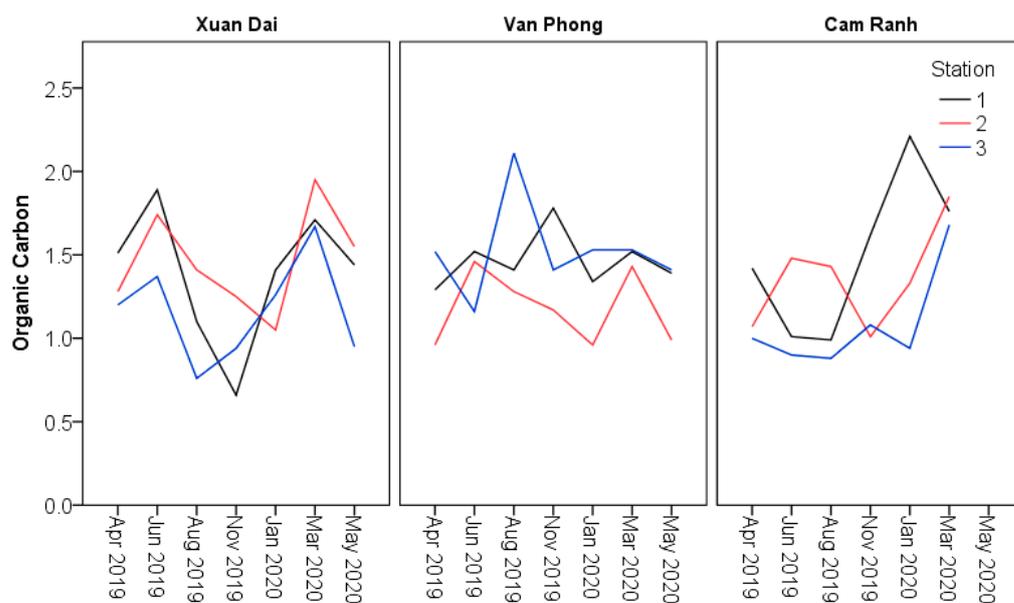


Figure 7. Variation of organic carbon (%) in sediment in each studied bay. Stations 1 and 2 within farming areas, and Station 3 as reference.

Total nitrogen (TN) concentrations in sediment were in the range of 281.8–836.2 mg/kg in Van Phong Bay; 246.4–838.4 mg/kg in Cam Ranh Bay; and 356.4–894.6 mg/kg in Xuan Dai Bay (Figure 8). Total phosphorus (TP) concentrations varied in the range of 132.0–427.2 mg/kg in Van Phong Bay; 128.8–446.9 mg/kg in Cam Ranh Bay; and 165.8–498.2 mg/kg in Xuan Dai Bay (Figure 9). The results showed that TN and TP concentrations of the farming areas of Cam Ranh Bay were significantly higher than those values in the reference station ($p < 0.05$), whereas in Van Phong Bay and Xuan Dai Bay, differences in TN and TP concentrations between farming areas and corresponding reference stations were insignificant ($p > 0.05$) (Figures 8 and 9).

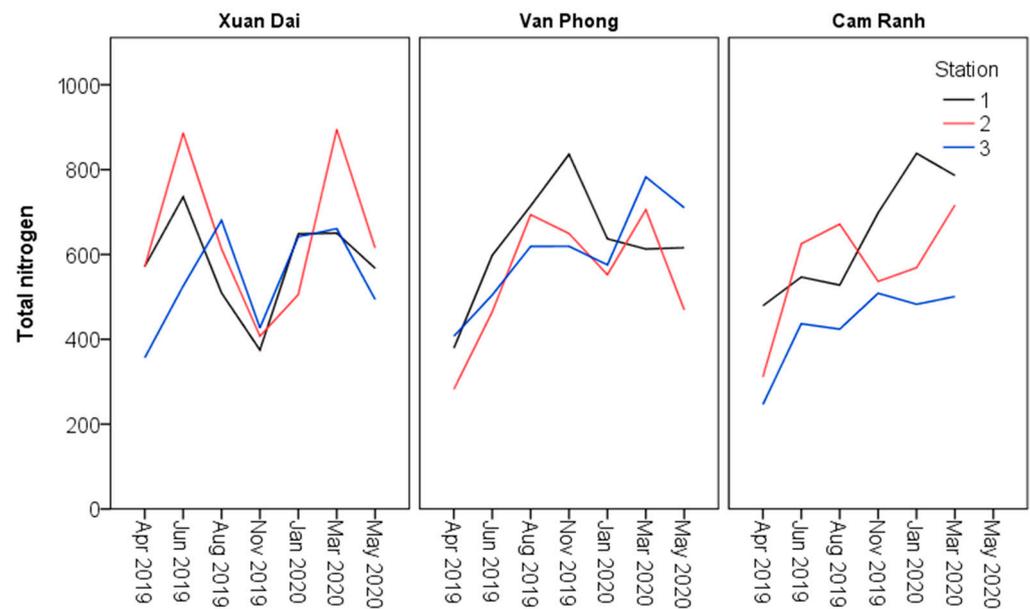


Figure 8. Variation of total nitrogen (mg N kg^{-1}) in sediment in each studied bay. Stations 1 and 2 within farming areas, and Station 3 as reference.

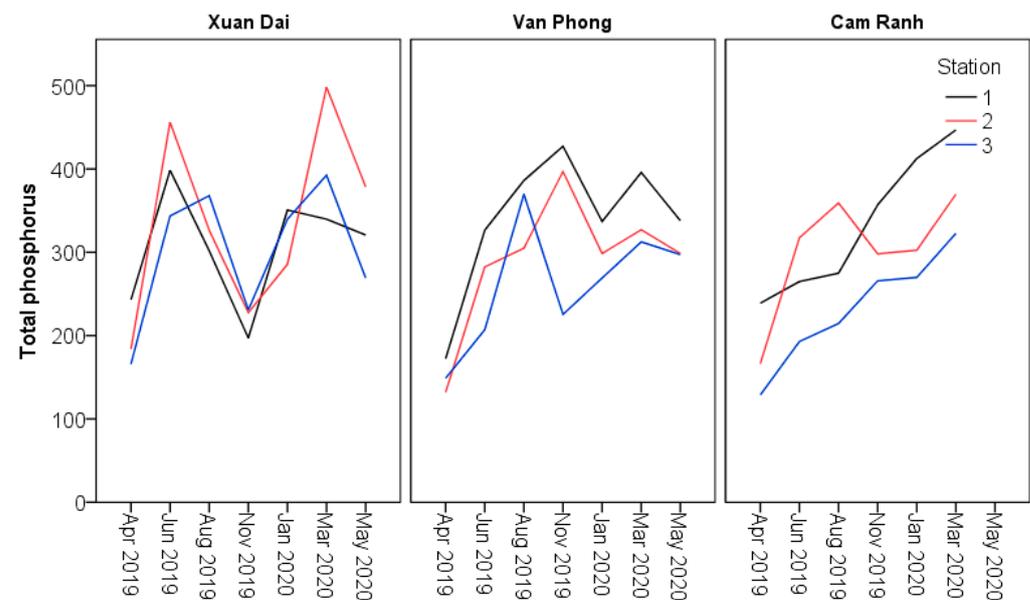


Figure 9. Variation of total phosphorus (mg P kg^{-1}) in sediment in each studied bay. Stations 1 and 2 within farming areas, and Station 3 as reference.

4. Discussion

The South-Central region of Vietnam has remained the center of mariculture, in which the majority of locations are ponds on coastal lands and cages in the coastal waters [55], such as shrimp pond culture [56], lobster cages culture [36], and finfish culture [57]. Mariculture has brought about many benefits for local people and seafood production for domestic and export demands. The mariculture sector also faces numerous issues including its impacts on the environment [55], such as reducing water quality and biodiversity in coastal waters [35,37].

In this study, environmental water quality was monitored in three bays (Xuan Dai, Van Phong, and Cam Ranh bays) over a 14-month period. The parameters of nutrients and BOD₅ had a variation in seasonal and annual cycles with the pattern of the lowest value in April and the highest value in November, whereas the TN and TP fluctuated. The

changes might be related to the phytoplankton cycles. The concentration of phytoplankton declined from January to April and increased from August to the end of the year with the peak in November and December [58]. Our observation was similar to that of previous studies [59,60]. No significant difference in water quality was observed between the farming areas and the reference (non-farming) stations. This could be attributed to dissolved components being diluted and assimilated by the pelagic ecosystem [61]. The distribution of water quality parameters in coastal waters was influenced by tidal and hydrodynamic regimes, the geomorphology of the coastline, infrastructures inside the waters, and changes following by the natural biological cycles, for example, phytoplankton growth cycles.

Xuan Dai, Van Phong, and Cam Ranh bays were semi-closed and/or enclosed [62] and lacked freshwater resources from inland [60] (Table 5). Therefore, the water exchange times fluctuated in the range of 5–67 days [63–65]. These bays are located in the regions of mixed and mainly diurnal tide [66] with tidal amplitudes of 68–263 cm (average of 124 cm). The tidal current was supported by water exchange in Van Phong Bay of 34.7% per day [67] and Cam Ranh Bay of 16.64% per day [65]. The tidal current velocity reached 59.8 cm/s at ebb tide and 71.9 cm/s at flood tide in Van Phong Bay [68] and 81.6 cm/s at ebb tide and 57.9 cm/s at flood tide in Cam Ranh Bay [65], whereas current velocity in Xuan Dai Bay's velocity was in the range of 8.8–45.0 cm/s, with an average of 26.1 cm/s in March 2022 (Chung, 2022, personal data). The high tidal amplitudes and current support water exchanges as well as material balance (environmental parameters) in and out of the bays. As a result, water environmental quality in these bays was found to still be suitable for aquaculture.

Table 5. Hydrodynamic features in Xuan Dai Bay, Van Phong Bay and Cam Ranh Bay.

Factors	Unit	Xuan Dai Bay	Van Phong Bay	Cam Ranh Bay	References
Area	km ²	60.8	425	71.1	[62]
Ave./Max. depth ¹	m/m	11/18	16/32	10/24	[62]
Type of bay		Semi-closed	Semi-closed	Enclosed	[62]
Size of gate: Width/Max. depth ²	km/m	4.5/18	17/30 0.25/32	3/24	[60]
Water exchange times	Day	5–29	43–61	15–67	[63,65]

Note: ¹: Ave./Max. depth—11/18: Average depth of bay: 11 m, and Maximum Depth of bay: 18 m; ²: Size of gate: Width/Max. depth—4.5/18: Width of gate: 4.5 km, and Maximum Depth of gate: 18 m.

Bouwman et al. [25] revealed that mariculture could release nutrients with an increase of up to sixfold by 2050, with an increase in marine eutrophication [26]. The accumulation of waste from mariculture in water bodies over time, especially from using low-valued fish in lobster culture with a feed conversion ratio of 28–42 [37,55] and the feed waste discharged directly into the sea [59], could increase nutrients of nitrogen and phosphorus [69] and cause algal blooms [28–31]. Doan-Nhu et al. [30] reported an algal bloom event in Van Phong Bay with cell densities reaching 3.9×10^6 cells·L⁻¹, contributing greatly to the mortality of fish or other marine fauna.

The input of organic matter to sediment originates from natural or artificial sources, causing changes in chemical and physical characteristics [70]. The environmental impact on the sediment from aquaculture depends on local environmental conditions (bottom depth, topography, and wave height) and management methods (stocking density, feeding rates) [69]. Redox potential values of −100 mV to −150 mV indicate that the sediments are polluted with organic matter [71]. The results in the present study were higher than those values in the other studies [71,72]. This suggests that the redox conditions of sediments were favorable for oxidation, leading to the low total sulfide contents in sediments. The total sulfide concentrations in the present study were lower than those in the studies of

Tsutsumi et al. [73] and Hamoutene [74]. However, the average sulfide concentration in Cam Ranh Bay was over the value of the USA's standard for sediment [52].

At Cam Ranh Bay, a significant difference in sediment quality (Org C, TN, TP) was observed between farming areas and the reference station ($p < 0.05$), whereas the same pattern was not detected in the sediments of the Van Phong and Xuan Dai bays ($p > 0.05$). It could be explained by the physical characteristics of the bays. Cam Ranh Bay has an enclosed water structure, whereas the Van Phong and Xuan Dai bays are semi-enclosed (Table 4). Therefore, the wave energy of Cam Ranh Bay is weaker, so the wave height is usually lower than the other bays. In Cam Ranh Bay, with weak wave energy, solid waste from cage farming is more likely to reach the bottom near the waste sources, leading to the local accumulation of waste materials on the seabed. On the other hand, in the Van Phong and Xuan Dai bays, which are more open, the effluent from area for farming may be dispersed over a larger area. This view is supported by studies by Cromey et al. [75]. The types of culture methods may also account for the difference in sediment quality. However, data on fish stocks, types of food, and feeding rates were not collected in the present study. These data would help to further understand the environmental impact of aquaculture activities in these bays.

The capacity for natural self-purification processes in coastal waters could help to recover the balance of water and sediment factors. However, if the volume of waste is excessive, these balances could change following an unfavorable trend. Due to hydrodynamic systems, the environmental parameters could also cause impacts on the adjacent waters. According to Pérez et al. [34], cage culture feed waste could impact a region of 20.6–22.6 ha with the fluxes of 1.9–2.8 kg m⁻² year⁻¹, whereas the total waste could impact a region of 21.8–27.5 ha with fluxes of 3.0–3.4 kg m⁻² year⁻¹. However, the accumulation and impacts of waste from mariculture are dependent on the water exchanges of shallow waters, and close, semi-open, and open water [8]. Organic matter accumulated over a relatively small surface of sediment could possibly generate hypoxic/anoxic conditions [8], likely increasing the sulfide concentration in this study. All of these factors could negatively impact the surrounding waters.

Furthermore, the change in environmental quality in lobster farming areas also depends on the socio-economic conditions in the farming area and the techniques applied to cage lobster farming. Although farmers could perceive that the increased practical and technique efficiency, and expanding regions of lobster cage farming put pressure on environmental quality [76], no or little improvements are being implemented. Ton Nu Hai and Speelman [77] identified risks for cage lobster farming such as unstable seeds, unstable feed, recent frequent disease and increased mortality, underdeveloped farming technology, and threats including decreased coastal resources, reliance on the Chinese market, less access to credit, lack of sanctions, and the complex development of diseases. Even if commercial feed was applied to cage lobster farming [50], the growing supply of low-valued fish from local fisheries was also important for the expansion of farming areas [77]. As a result, environmental quality is degraded due to released nutrients from unused feed and waste from cage lobster farming. Thus, Nguyen [35] noted the overload of mariculture capacity in coastal waters due to the development of lobster cage culture. Thus, the increase in the number of cages in lobster culture caused the outbreak of disease and mass mortality in cultured lobster [78,79]. As a result, water and sediment quality could be reduced over time if mariculture expands in terms of environmental capacity in coastal waters [69,80].

5. Conclusions

This paper examined the changes in water and sediment environmental quality in lobster cage farming regions in Xuan Dai Bay, Van Phong Bay, and Cam Ranh Bay in South-Central Vietnam. Despite a difference in the development history of lobster cage farming in these regions, changes in water environmental quality are insignificant within farming areas, but nutrients and BOD₅ change seasonally and depend on organism cycles

and the hydrological and dynamical regimes in each region. In general, in areas with good water exchange (as in the case of Van Phong Bay), cage lobster farming may not cause serious changes in the aquatic environment within the bay. However, material, mainly organic matter, accumulated from caged lobster farming on bottom sediments could have a major impact on the environment (such as the sulfide concentration in Cam Ranh Bay). Normally, the mineralization process of organic matter accumulated on the bottom occurs gradually, but as the bed was disturbed, the rate of material mineralization increased, resulting from the sources of nutrients for the water bodies. The aquatic environment could lead to eutrophication. Combined with favorable natural conditions, algae would grow and bloom. On the other hand, if the number of lobster cages/rafts increased over the environmental carrying capacity of the waters, several environmental problems would occur continuously and simultaneously. Environmental degradation in the mariculture area and their consequences might affect the outcomes and livelihoods of local farmers directly, or indirectly with regard to other local communities such as fishermen. Moreover, mariculture could also be the cause of conflicts in the development of economic sectors due to the limitation of marine resources and marine space.

In order to ensure sustainable lobster cage farming in the South-Central marine regions of Vietnam, it is important to continue monitoring the changes in water and sediment quality. A set of better management practices needs to be developed based on the monitoring data, and deployed to farmers to facilitate changes in farming practices to ensure minimal impacts on the environment.

Author Contributions: Conceptualization, P.M.-T. and P.T.K.-H.; methodology, L.H.P., P.T.K.-H., T.V.C. and T.V.B.; software T.V.B.; validation, P.T.K.-H., A.L.N. and P.M.-T.; formal analysis, L.H.P., L.T.D., N.H.T. and P.H.N.; investigation, L.H.P., L.T.D., A.L.N., N.T.T.T. and N.T.H.A.; resources, P.T.K.-H.; data curation, P.T.K.-H., P.M.-T., L.H.P., P.H.N., N.T.T.T. and N.T.H.A.; writing—original draft preparation, L.H.P., P.T.K.-H., A.L.N. and P.M.-T.; writing—review and editing, P.T.K.-H., A.L.N. and P.M.-T.; visualization, P.M.-T.; project administration, P.T.K.-H.; funding acquisition, P.T.K.-H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by VAST project of “Using biological indicators to assess environmental impacts of coastal cage aquaculture in South Central Vietnam”, grand number: VAST06.03/19-20.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank Thuy Nguyen, DataGene Ltd., Melbourne, Australia and Brett Ingram, Victorian Fisheries Authority, Australia for improving the English and editing the manuscript. We would like to thank the project “Upgrading station for marine environment monitoring and analyzing in southern region of Vietnam” for providing their equipment. This paper is a contribution to celebrate the 100 years Anniversary of the Institute of Oceanography, Vietnam Academy of Science and Technology.

Conflicts of Interest: The authors declare no conflict of interest.

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