

Article

Phosphorus Species, Influencing and Release Risks Assessment in Mangrove Wetland Sediments of Dongzhai Harbor on Hainan Island, China

Gucheng Zhang ^{1,2,3}, Guicheng Xue ^{1,2,*}, Ming Ruan ^{2,*}, Yusheng He ², Di Lin ² and Sumin Du ¹

¹ Hainan Key Laboratory of Marine Geological Resources and Environment, Haikou 570206, China

² Hainan Geological Survey Institute, Haikou 570206, China

³ School of Earth Sciences, China University of Geosciences, Wuhan 430074, China

* Correspondence: 13876097165@163.com (G.X.); ruanming2022@126.com (M.R.)

Abstract: Mangrove wetlands are superior sites for the deposition of various pollutants, but they are also more susceptible to environmental contamination. To investigate the health threats of phosphorus to mangrove ecosystems, this study presents the distribution, chemical speciation and factors influencing phosphorus (P) forms in 38 surface sediments from the mangrove wetlands of Dongzhai Harbor on Hainan Island, China. P forms were measured using the sequential extraction (SEDEX) procedures. The results showed that the total phosphorus content in the sediment was at a high level, and there was a significant spatial variability of phosphorus in each form. Among them, inorganic phosphorus accounted for 74.64% of the total phosphorus, and organic phosphorus accounted for 25.35% of the total phosphorus. Among the inorganic phosphorus, detrital limestone phosphorus and Ca-bound phosphorus were dominant, while the content of exchangeable phosphorus and Fe-bound phosphorus had a smaller percentage. The concentration of biologically available phosphorus, ranged from 1.76 $\mu\text{mol/g}$ to 18.57 $\mu\text{mol/g}$, and the Fe-bound and organic forms of phosphorus had a controlling effect on it. Based on C_{org}/OP , N/P and land use surveys, it was concluded that phosphorus was mainly an exogenous input. The correlation analysis concluded that the main sources of phosphorus in the study area are agriculture and aquaculture. The development of agriculture and aquaculture led to moderate levels of phosphorus pollution in the study area as a whole, with more serious a phosphorus pollution at the wetland park in the southeast corner of Dongzhai Harbor and in the western areas, with lush vegetation and developed river systems, mainly influenced by human activities, topography, vegetation and water system conditions.

Keywords: Dongzhai Harbor; mangrove forest; sediment; phosphorus species; pollution risk



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1. Introduction

Mangrove forests are intertidal forests with adjacent watercourses, which grow in warm temperate, subtropical and tropical coastlines [1,2]. Because of the joint action of marine and terrestrial ecosystems, wetlands are able to receive large amounts of phosphorus from tides, river water, and surface runoff, so mangrove wetlands have become important phosphorus storage and sink sites [3] and play an important role in the biological productivity of estuarine and coastal environments [4]. With the development of wetlands, industrial and agricultural wastewater and domestic sewage from human activities have contributed large amounts of phosphorus to wetlands, creating a phosphorus “source” that has caused numerous ecological impacts in wetlands and coastal ecosystems [5,6]. For example, nutrient-rich mangroves may capture less sediment and absorb less nutrients than nutrient-poor mangroves, thus affecting the ecology of the coastal waters [7]. The increase of phosphorus concentration may cause intensive growth of benthic and planktonic algae, which can cause changes in the structure of biological communities, as well as a decrease in water quality [8]. In addition to human disturbances, the physico-chemical

properties of sediments equally influence the distribution of different forms of phosphorus content [9,10]. In flooded conditions, anaerobic conditions in sediments may promote the release of P from phosphates [11]. The increase of microbial activity will lead to the decomposition of organic matter, which will affect the processes of phosphorus cycling in the coastal environments [12]. In wetlands, a high production and retention of organic matter can promote the enrichment of phosphorus, especially organic phosphorus [13]. The input and burial of various forms of phosphorus to wetlands is considered as a complex interplay of geochemical processes. Therefore, it is necessary to study the distribution of phosphorus forms in mangrove wetland sediments for understanding the geochemical cycling of phosphorus and preventing eutrophication in aquatic ecosystems.

In recent years, with the rapid socio-economic development around the coastal zone, mangrove forests located on estuarine shores have been subjected to widespread and severe ecologically destructive development activities, and the health of the sustainably used resources and environment of estuarine shores are under great threat [14]. The rapid development of aquaculture, tourism and urban construction in Hainan Island, China, especially in the coastal areas of Hainan Island, has led to a dramatic decrease in the mangrove area and also to the weakening of the mangrove ecological functions [15,16], which have provided superior conditions for nutrient pollution. However, there are few studies on phosphorus species in sediments from coastal areas, and there are almost no systematic studies on phosphorus species, influencing factors and sources of phosphorus in sediments, concerning the Hainan region, especially the mangrove coastal wetlands with rapid economic development. In order to fill this knowledge gap and provide a comprehensive overview of the phosphorus geochemistry in the study area, this study was carried out to analyze the phosphorus morphological content, spatial distribution characteristics, and influencing factors of the mangrove wetland sediments in Dongzhai Harbor, Hainan, and to investigate the sources of phosphorus [17], which will help to evaluate the ecological environment of mangrove wetlands, understand the material migration, grasp the evolution of phosphorus cycling in coastal areas, and provide theoretical support for the conservation of mangrove ecosystems.

2. Materials and Methods

2.1. Study Area and Sampling

Hainan Dongzhai Harbor National Nature Reserve is located at the junction of Haikou City and Wenchang City in Northeastern Hainan Province (Figure 1), and is the first nature reserve of mangrove wetlands established in China. The wetlands have a tropical maritime monsoon climate, with an average annual precipitation of 1676 mm, irregular all-day tides and an average tidal difference of about 1 m. The Dongzhai Harbor is funnel-shaped deep inland, surrounded by sea on three sides, and is a semi-enclosed sea area with poor water exchange conditions. The low topography of the wetlands carries sediment to be deposited in the harbor with the water system from the east, west and south directions respectively, and forms mudflats, which provides habitat for the ecosystem and also provides conditions for the enrichment of nutrient salts [18]. The total area of the wetlands is about 360 km², with the largest proportion of paddy fields and woodlands, followed by rivers and mudflats, and the smallest proportion of construction land. Due to the intensive human activities, many threats have been brought to the local ecological environment, and the mangrove environment has been damaged to some degree. In this study, based on the geographical distribution characteristics and mangrove distribution of Dongzhai Harbor in 2020, 38 survey stations (HS01–HS38) with a distribution area about 18 km² were set up and sampled for analysis (Figure 1). During the sampling process, it was important to ensure that the surface layer was not significantly disturbed by the sampler, which was vertical and as slow as possible, to take the complete mud core at one time to keep the longitudinal integrity of the samples.

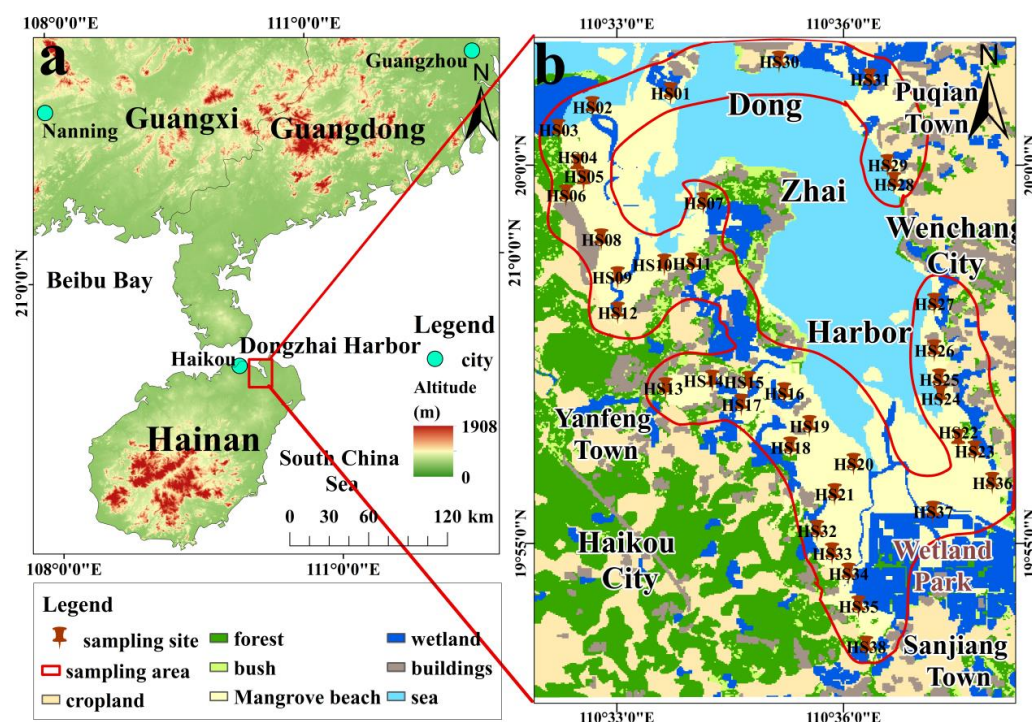


Figure 1. Map showing the study area (a) and sampling points (b).

2.2. Extraction Method for Phosphorus and Other Elements

We used the modified SEDEX method to test and determine the different fractions of P, which was divided by extraction order into [17]: exchangeable phosphorus (Ex-P), Fe-bound phosphorus (Fe-P), authigenic Ca-bound phosphorus (Ca-P), detrital limestone phosphorus (De-P), and organic phosphorus (OP). Among them, the inorganic phosphorus (IP) content was the sum of the exchangeable phosphorus (Ex-P), Fe-bound phosphorus (Fe-P), authigenic Ca-bound phosphorus (Ca-P) and detrital limestone phosphorus (De-P). The sum of IP and OP was TP. Following each extraction step, $MgCl_2$ was used for successive washes to prevent secondary adsorption onto the residual sedimentary matrix. Finally, the supernatant obtained was collected for analysis and determination by spectrophotometric method. Each sample was measured three times in parallel, and the average value of each form of phosphorus was taken, and the relative deviation of each form of phosphorus content was within 10%.

Organic carbon was determined by placing a weighed 0.1 g sediment sample on a ceramic tray and adding two drops of 1 mol/L hydrochloric acid solution until the sediment sample was no longer bubbling. The pre-acidified sample was dried in an oven at 105 °C. The sample was removed and cooled, and the organic matter was determined using the MultiN/C2100 TOC (Analytik Jena, Jena City, Germany) tester solids module feed.

Nutrient N was determined by weighing 1.5 g of the ground sediment sample, putting it into a digestion tube, adding a digestion tablet and 12 mL of concentrated sulfuric acid, and making a blank sample at the same time. The sample was digested in the digestion oven at 420 °C for 2 h, then 30 mL of distilled water was added to the sample after it was cooled, and the results were determined using an automatic analyzer.

The analysis of the trace element content in the soil in this study was mainly performed by ICP-OES with the same analytical method as Li et al. [19].

2.3. Statistical Analysis

In this study, we mainly used Arcgis 10.7 (Esri, RedLands City, CA, USA) to analyze the spatial concentration distribution of each element. SPSS 23 (IBM, Armonk City, NY, USA) was used to count and analyze the data, and Origin Pro 2021 (OriginLab, Northampton City, MA, USA) was used to make graphs.

2.4. Contamination Evaluation

At present, there are no unified standards and methods for a nutrient ecological risk evaluation at both home and abroad, and the most widely used method is the single-factor pollution index evaluation method, proposed by the Ministry of Environment and Energy of Ontario, Canada. Therefore, in this study, the pollution index method was used to evaluate the degree of phosphorus pollution in the study area with the following equation [20]:

$$S_i = \frac{C_i}{C_s}$$

where, S_i is the pollution index of TP; C_i is the content of TP (mg/kg) and C_s is the standard value of TP in regional sediment. In this study, we used the TP threshold (600 mg/kg), which causes the lowest level of ecological risk effect, as the standard value [21]. The evaluation criteria of S_i are shown in Table 1.

Table 1. Evaluation criteria for the nutrient pollution status in the sediments.

S_i	Contamination Level
<0.5	Clean
0.5~1.0	Mild contamination
1.0~1.5	Moderate contamination
>1.5	Severe contamination

3. Result

3.1. General Characterization of the Studied Sediments

The content of organic carbon (C_{org}), N and P in the study area, varied from 0.20% to 4.05%, 205.12 mg/kg to 2618.76 mg/kg, 146.18 mg/kg to 2078.13 mg/kg, with the average values of 1.7%, 1097.05 mg/kg and 725.65 mg/kg, respectively. All of these exceeded the background values given in The Chinese Soil Elemental Background Values [22]. The coefficients of variation of C_{org} , N, and P were 60.93%, 55.60%, and 58.44%, respectively, and all of these were ranked as strong variations [23] (Table 2). Based on the contents, the coefficients of variation and the range of variation of the three types of nutrients, it could be concluded that the distribution of C_{org} , N and P is strongly influenced by the environment. In terms of spatial distribution, the three types of nutrients were mainly distributed in areas with high vegetation and anthropogenic activities, equally indicating that nutrients are not only influenced by natural conditions but also have some relationship with anthropogenic interventions (Figure 2). In particular, the nutrient concentrations at HS13, HS14 and HS38 were generally higher than those at other sites, and the P concentration at HS14 even reached 2078.13 mg/kg. Therefore, it is necessary to pay more attention to the distribution of the nutrient concentrations and the formation mechanism at these sites.

Table 2. General characterization of the studied sediments.

	N (mg/kg)	P (mg/kg)	C_{org} (%)	Fe (mg/kg)
maximum	2618.76	2078.13	4.05	8120.00
minimum	205.12	146.18	0.20	146,790.00
mean	1097.05	725.65	1.70	37,707.89
standard deviation	609.99	424.05	1.03	24,771.33
coefficient of variation (%)	55.60	58.44	60.93	65.69

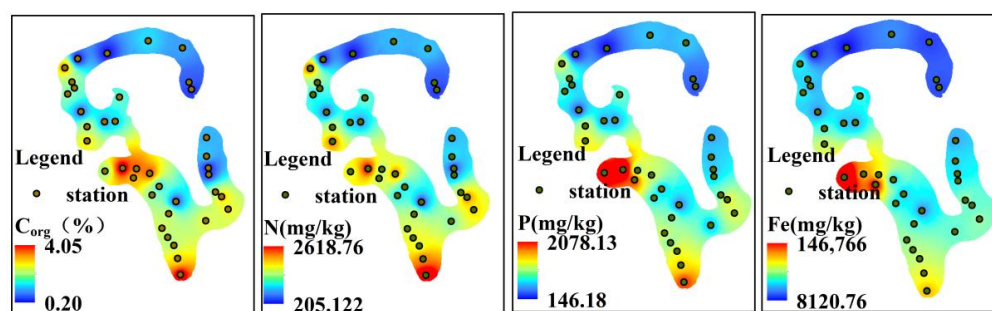


Figure 2. Spatial distribution of the regional sediment physicochemical properties.

The total Fe content in the sediment ranged from 8120 to 146,790 mg/kg, with the average value of 37,707.89 mg/kg and the coefficient of variation of 65.69%, which indicated that Fe was in a strong variation state and was influenced by the environment (Table 2). In terms of the spatial distribution, the high Fe content was mainly distributed in areas with multiple vegetation and anthropogenic activities, and the overall distribution was similar to the nutrient's concentration (Figure 2).

3.2. Spatial Distribution Characteristics of the P Species

Phosphorus forms are mainly classified into inorganic phosphorus (exchangeable phosphorus, Fe-bound phosphorus, Ca-bound phosphorus, primary detrital phosphorus) and organic phosphorus [17]. In this study, the different forms of phosphorus in the study area were analyzed and the distribution of the content at each station was obtained (Table 3, Figure 3): the content (range, mean) of exchangeable phosphorus (Ex-P), Fe-bound phosphorus (Fe-P), Ca-bound phosphorus (Ca-P), primary detrital phosphorus (De-P), organic phosphorus (OP) and total phosphorus (P) ($\mu\text{mol/g}$) ranged from 0.24 to 1.26, 0.86; 0.49 to 3.75, 1.64; 1.23 to 10.52, 4.8; 1.69 to 19.43, 7.8; 1.03 to 13.75, 5.13; 4.72 to 47.48, 20.23, respectively. The relative contribution of each form of phosphorus to total phosphorus was ranked as $\text{De-P} > \text{OP} > \text{Ca-P} > \text{Fe-P} > \text{Ex-P}$, where IP accounted for the largest component of the total phosphorus (74.64%), while the contribution of OP was relatively small (25.35%). Among the four IPs, De-P was the dominant component, especially in HS15, HS17, HS19, HS28, HS29 and HS38, with the highest percentage monitored, accounting for more than 40% of the total phosphorus; followed by Ca-P, which was detected in HS36, in particular, accounting for more than 30% of the total phosphorus; Ex-P and Fe-P accounted for a smaller percentage of the total at each site. The coefficients of variation of Ex-P, Fe-P, Ca-P, De-P, OP, and P were 37.88%, 59.70%, 61.38%, 62.20%, 66.88%, and 59.75%, respectively, with a strong spatial differentiation, and each form of phosphorus was more than 36%, indicating an extremely strong environmental influence. Ex-P, Fe-P and OP can be further categorized as bioavailable phosphorus (BAP), within the wetlands, the concentration ($\mu\text{mol/g}$) of BAP ranged from 1.76 to 18.57, accounting for more than 37.8% of the total phosphorus on average.

Table 3. Phosphorus species content.

Phosphorus Species ($\mu\text{mol/g}$)		Maximum	Minimum	Mean	Standard Deviation	Coefficient of Variation (%)	Proportion (%)
IP	Ex-P	35.00	0.56	5.31	9.03	170.03	0.85
	Fe-P	295.06	14.16	129.87	85.32	65.69	20.73
	Ca-P	187.57	3.75	47.72	51.12	107.14	7.62
	De-P	269.77	27.52	106.39	67.79	63.71	16.98
OP		747.93	94.95	337.32	188.47	55.87	53.83
TP		1470.5	146.1	626.61	374.30	59.73	100.00

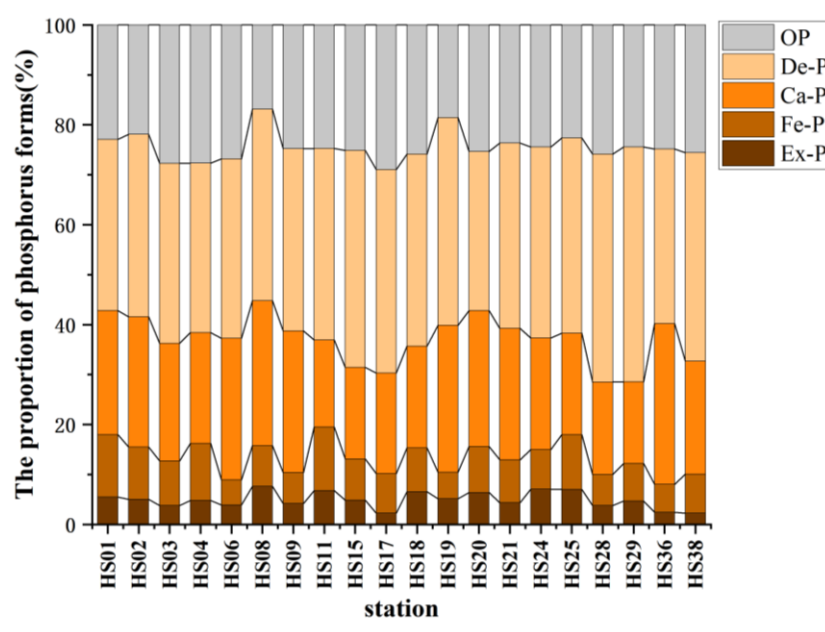


Figure 3. Percentages of the various P forms in surface sediment at each station.

The spatial distribution of the different forms of phosphorus was similar (Figure 4). High concentrations of Ex-P, Fe-P, Ca-P, De-P, OP, IP, and BAP mainly distributed in areas where dense vegetation existed, around HS03, HS04, HS09, HS17, HS21, HS36 and HS38, similar to the spatial distribution of C_{org} , N, P and Fe, while showing a sharp contrast with the distribution of various forms of phosphorus on the light beach. During the investigations, it was also found that high concentrations of Ex-P, Fe-P, Ca-P, De-P, OP, IP and BAP were mainly near the range of human activities. Therefore, it could be speculated that the enrichment of different forms of phosphorus should be equally inextricably related to human activities, in addition to the possible correlation with vegetation.

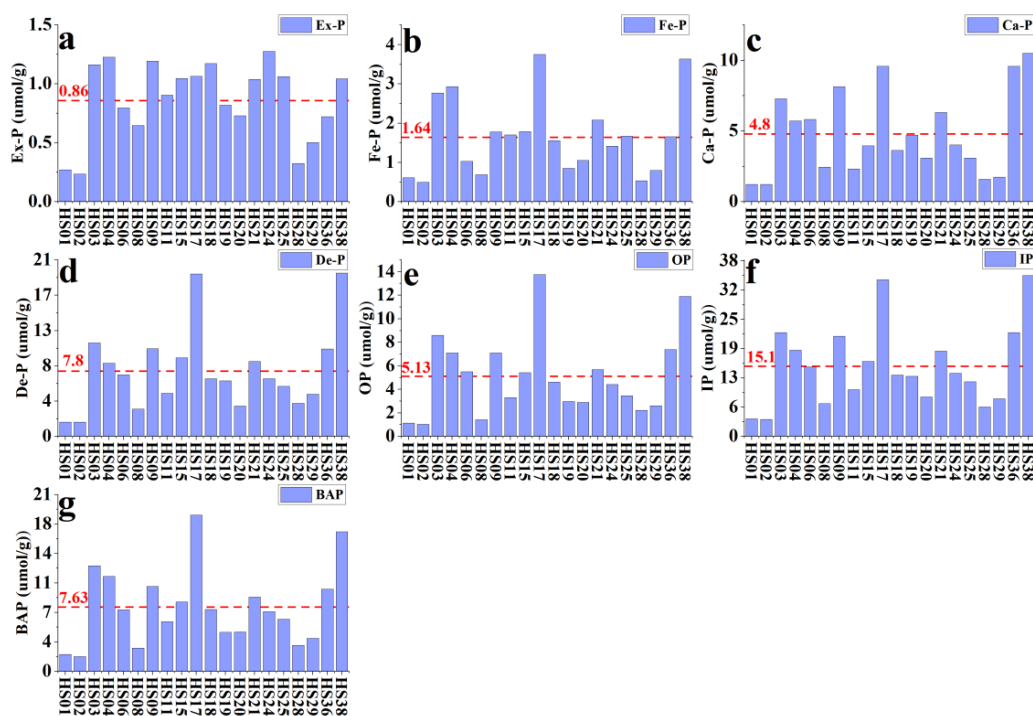


Figure 4. Spatial distribution of (a–f) the different P species and (g) bioavailable P (BAP) in surface sediments from the Dongzhai Harbor.

4. Discussion

4.1. Analysis of Phosphorus Sources and Influencing Factors

Ex-P is phosphorus with a weak adsorption to attached materials, which can be converted into soluble phosphorus at a certain extent, and such phosphorus is easily released and used by organisms [24]. It could be found in the elemental correlations (Table 4), that Ex-P showed significant positive correlations with N, P, Fe and C_{org}, with correlation coefficients greater than 0.5, relatively high Ex-P values are usually associated with high phosphorus input from rivers or coastal effluents [25]. According to the land use survey, it was found that the surrounding of Dongzhai Harbor wetlands is dominated by agriculture and aquaculture, which put a lot of nutrients into the wetlands, therefore, this is one of the reasons for the high correlation between Ex-P and N, P and C_{org}. Organic matter may be an important factor in regulating Ex-P concentrations [26]. Therefore, this explained the generally high correlation between Ex-P and C_{org} content. Ex-P is easily adsorbed on sediment mineral surfaces. Therefore, Ex-P showed a positive correlation with Fe [27].

Table 4. Correlation between the phosphorus species and other variables.

	Ex-P	Fe-P	Ca-P	De-P	OP	TP	IP	BAP	N	Fe	C _{org}
Ex-P	1										
Fe-P	0.69 **	1									
Ca-P	0.56 **	0.78 **	1								
De-P	0.59 **	0.90 **	0.90 **	1							
OP	0.60 **	0.92 **	0.91 **	0.97 **	1						
TP	0.63 **	0.91 **	0.94 **	0.98 **	0.99 **	1					
IP	0.63 **	0.90 **	0.95 **	0.98 **	0.98 **	0.99 **	1				
BAP	0.67 **	0.96 **	0.89 **	0.97 **	0.99 **	0.98 **	0.97 **	1			
N	0.56 **	0.80 **	0.88 **	0.85 **	0.84 **	0.88 **	0.89 **	0.84 **	1		
Fe	0.58 **	0.82 **	0.77 **	0.92 **	0.89 **	0.89 **	0.89 **	0.89 **	0.66 **	1	
C _{org}	0.55 *	0.79 **	0.80 **	0.84 **	0.83 **	0.85 **	0.85 **	0.83 **	0.91 **	0.76 **	1

* Significant correlation at $p < 0.05$. ** Significant correlation at $p < 0.01$.

Fe oxide/hydroxide in sediments can trap or release phosphate, in response to changes in the redox environment [28]; Ca-P mainly represents phosphorus bound to CaCO₃, including biogenic apatite (bones, teeth, shell fragments and calcareous phytoplankton, etc.) and authigenic carbonate fluorapatite [29]; De-P includes detrital apatite and other phosphorus-containing minerals [30], which may be formed from Ex-P, Fe-P and phosphate released from OP, but its formation is slow [31]; OP is considered to be the source of dissolved phosphate present in the sediment interstitial water, due to bacterial regeneration [25]. It showed a highly significant positive correlation between Fe-P, Ca-P, De-P and OP in the correlation analysis (Table 4), indicating similar sources as well as deposition patterns. Fe-P, Ca-P, De-P and OP showed a high correlation with Ex-P as well, indicating that these four forms of phosphorus were of similar origin to Ex-P and may be related to the surrounding agriculture as well as aquaculture. On Hainan Island, domestic sewage has been identified as one of the main sources of irrigation water [32]. Based on the distribution of phosphorus concentrations, it could be assumed that partial sources of different forms of phosphorus in wetland sediments may also come from domestic wastewater. It has also been revealed that domestic wastewater was rich with nutrients, which had a significant effect on the enrichment of different forms of phosphorus [13]. Thus sewage discharges from residential areas, likewise brought significant effects on the phosphorus combination and transformation in wetlands. However, the proportional contribution of agricultural production and residential discharges to phosphorus could not be explored in detail so far and still needs to be further discussed in future studies.

It has been reported that the increase of organic matter and fine-grained sediment fractions in some areas would lead to the increase of OP [33]. In the description of the elemental content above (Figure 3), the distribution of Fe-P, Ca-P, De-P and OP was similar to that of C_{org}, and the correlation analysis also showed that Fe-P, Ca-P, De-P and OP were

positively correlated with C_{org} . So it could be further speculated that C_{org} played a controlling role on the phosphorus morphology distribution. Since the redox reaction of Fe was one of the main elements controlling the phosphorus adsorption/desorption from sediments [34], Fe played an equally important role in the control of the phosphorus morphology.

C_{org}/OP ranged from 20.60 to 197.46, with a mean value of 89.3, and the low value areas were all found near the light beach. N/P ranged from 0.6 to 2.05, with a mean value of 1.42 (Figure 5). (C:N:P = 106:16:1), proposed by Redfield, is widely used to determine the source of phosphorus [35]. Yang et al. [36] found that C_{org}/OP less than the ratio proposed by Redfield, is usually found in aerobic/anoxic areas characterized by low C_{org} , which are dominated by high amounts of insoluble organophosphorus or by bacterial organisms. The overall low C_{org}/OP in this study might represent the control of detrital organic matter by benthic organisms [15]; C_{org}/OP greater than the ratio proposed by Redfield, would indicate that OP was terrestrial in origin [35]. In this study, most of the C_{org}/OP near the light beach was less than 106 while most of the C_{org}/OP in the inland area was greater than 106, it could be assumed that phosphorus was mainly from terrestrial sources, especially agriculture and aquaculture, and controlled by the surrounding topographical conditions. N/P less than the ratio proposed by Redfield, indicates that phosphorus in the sediment is mainly an exogenous input [37]. In the description of N/P, in Figure 4, it was concluded that the N/P ratio is less than 16 at all points, which indicated that phosphorus in the sediment is mainly an exogenous input, and in the comparison with The Chinese Soil Elemental Background Values, above similarly indicated that phosphorus should be an input from sources other than natural sources [22]. In addition, according to the land utilization survey, Dongzhai Harbor is dominated by agriculture and aquaculture. In summary, the main sources of phosphorus in the wetland sediments would be agriculture and aquaculture.

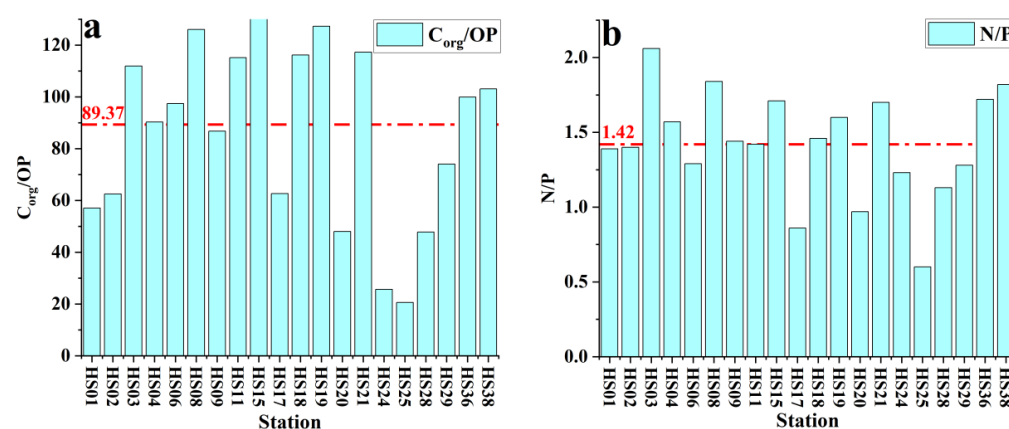


Figure 5. The results of (a) C_{org}/OP and (b) N/P ratios in the sediments.

4.2. BAP Release Risk

Ex-P is easily released from the sediment to the overlying water; Fe-P is also easily released from the sediment when the environmental redox conditions change; OP is biogeochemically active; therefore, Ex-P, Fe-P and OP are the main components of BAP [38], meanwhile, Ex-P, Fe-P and OP are all positively correlated with BAP (Table 4), which also reflects the mutual control of the three phosphorus species on BAP in this study. Compared with the east coast of Hainan Island [15], The overall concentration of Fe-P, OP and BAP in the mangrove wetlands of Dongzhai Harbor, Hainan was higher than that of the east coast, but the concentration of Ex-P was lower than that of the east coast (Figure 6). The influence of the water levels in Dongzhai Harbor and the east coast and the different land utilization patterns may be responsible for the large differences in the distribution of different phosphorus morphologies [39–41]. Comparison of the slopes from the linear regression showed that a lower slope was a higher correlation, therefore, the BAP concentration in the study

area was mainly controlled by Fe-P and OP, while the east coast was controlled by Ex-P. The reason for the difference with the study by Han et al. [41], is also related to the local agricultural, aquaculture and domestic wastewater discharges in the study area.

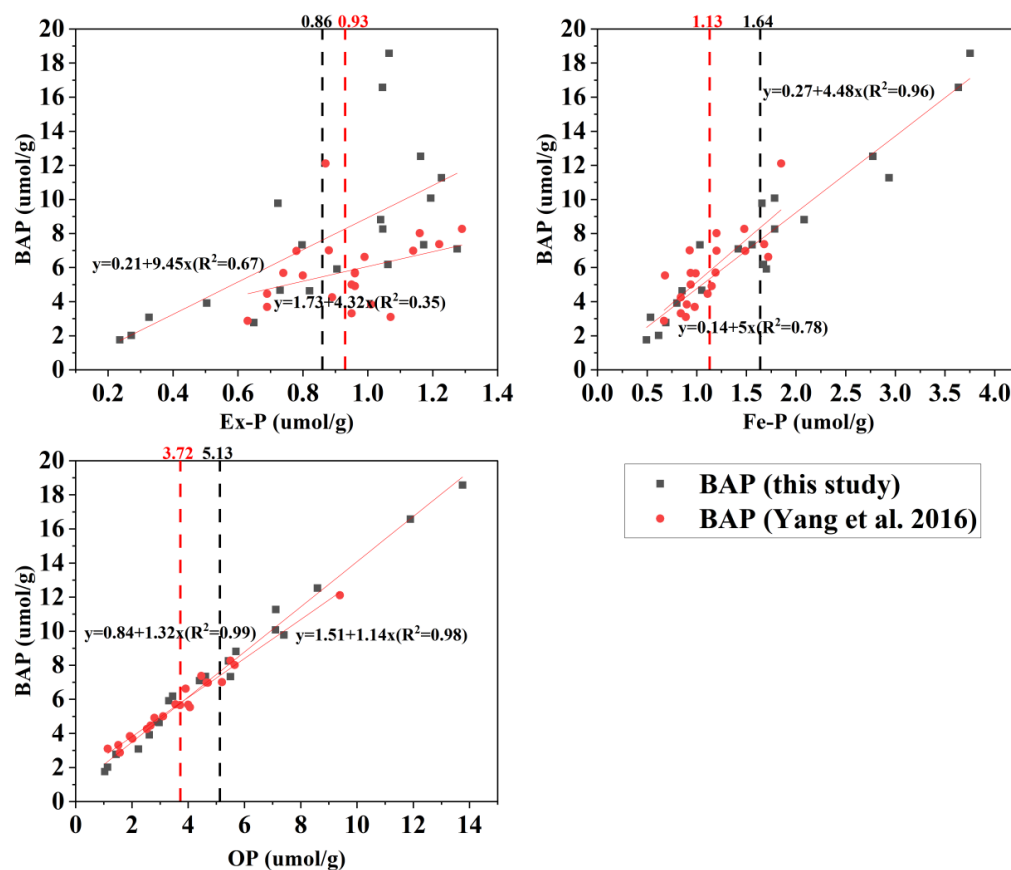


Figure 6. Relationship between BAP and Ex-P, Fe-P and OP in the surface sediments of the Dongzhai Harbor wetlands and the east coast of Hainan [15].

4.3. Phosphorus Pollution Evaluation

The phosphorus content in the study area exceeded the background values given in *The Chinese Soil Elemental Background Values* [22], so there was a possibility of phosphorus contamination. The evaluation of the bottom sediment phosphorus pollution index revealed [20] that the TP pollution index at 38 stations ranged from 0.24 to 3.46, with a mean value of 1.2, and the overall was at a moderate pollution level. In particular, there were four points at a clean level, accounting for 10.53% of the total points; 16 points at a light pollution level, accounting for 42.11% of the total points; eight points at a moderate pollution level, accounting for 21.05% of the total points, and 10 points at a heavy pollution level, accounting for 26.32% of the total points (Figure 7). According to the distribution of the phosphorus pollution index, most of the stations in the presence of pollution were located at the wetland park in the south-east corner and the location of rich vegetation and water conditions in the west of Dongzhai Harbor. Previous studies have shown [42] that the well-developed root system of mangrove plants can enrich all kinds of substances more easily than the general tidal flats. In addition, mangroves themselves also have the same strong primary productivity, thus, providing a large amount of phosphorus enrichment to mangrove wetlands. In a comprehensive view, except HS01, HS02, HS08 and HS28, other stations have been polluted to some extent. In particular, the 10 sites in the heavy pollution level posed serious threats to the ecological development and eutrophication of the wetlands. The phosphorus concentration in HS14 even reached 2078.13 mg/kg, which revealed the need to pay special attention to human disturbance and the natural influence on it in future prevention and monitoring. According to

the above discussion, firstly, the control of pollution sources, such as urban sewage and farmland runoff, needs to be carried out. Secondly, thematic studies on the quality of the marine environment need to be carried out. Then, natural aquaculture should be adopted instead of net box aquaculture. Finally, a reasonable and optimized spatial layout and functional zoning framework of the wetland environment should be established for the effective management of wetland sustainable development.

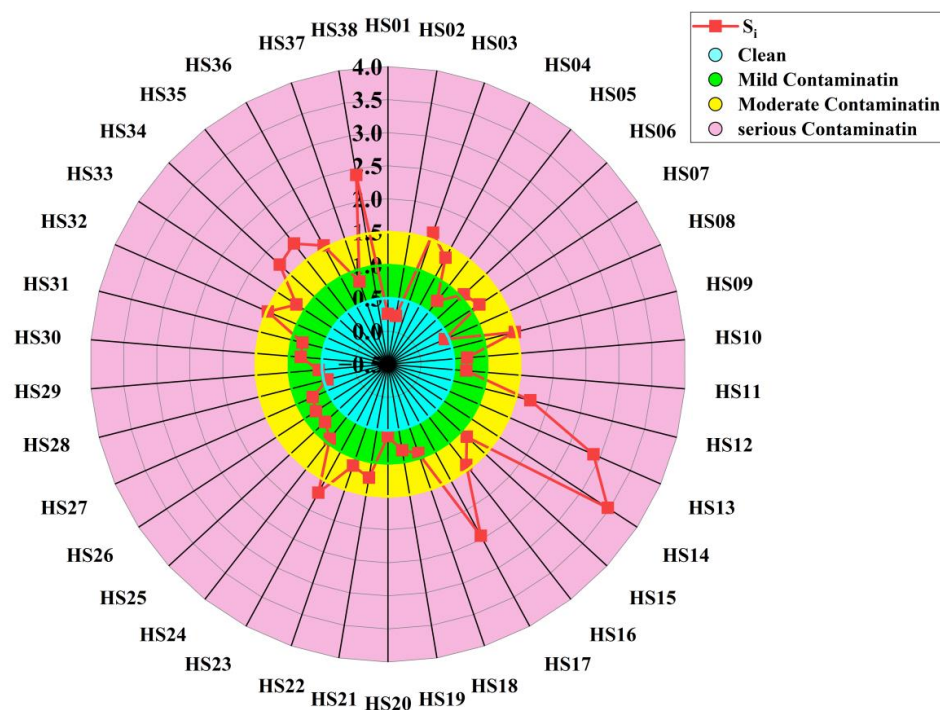


Figure 7. Total phosphorus pollution indices in sediments in the Dongzhai Harbor wetlands.

5. Conclusions

The total phosphorus content in the surface sediments of the mangrove wetlands in Dongzhai Harbor, Hainan, ranged from 146.18 mg/kg to 2078.13 mg/kg. IP accounted for the largest proportion of the total phosphorus, with 74.64%, while OP accounted for 25.35% of the total phosphorus. De-P and Ca-P were dominant in IP, while Ex-P and Fe-P accounted for a smaller proportion. Ex-P, Fe-P and OP could be classified as BAP. Within the wetlands, the concentration ($\mu\text{mol/g}$) of BAP, ranged from 1.76 to 18.57, accounting for more than 37.8% of the total phosphorus on average, and these three phosphorus species correlate well with BAP, reflecting their mutual control of BAP. There was significant spatial variability in each form of phosphorus influenced by the environment.

C_{org}/OP ranged from 20.60 to 197.46 and N/P ranged from 0.6 to 2.05, indicating that phosphorus is mainly input from exogenous sources. The correlation analysis showed that Ex-P, Fe-P, Ca-P, De-P and OP were positively correlated with N, P, C_{org} and Fe, again verifying that the main sources of phosphorus in the study area were agriculture and aquaculture, while C_{org} and Fe played an important role in the control of phosphorus forms. The BAP within the wetlands was much higher than that of the east coast of Hainan and was mainly controlled by Fe-P and OP, which was related to the local agriculture, aquaculture and domestic wastewater discharge in the study area.

The overall phosphorus pollution in the region was at a moderate pollution level, with higher pollution levels mainly in the wetland park in the southeast corner of Dongzhai Harbor and in the western areas with lush vegetation and developed river systems, which also indicated that phosphorus pollution was closely related to human activities, topography, vegetation and water system conditions. We need to pay special attention to the

distribution of the phosphorus content under these conditions in future wetland pollution control efforts, and take measures to avoid ecological health impacts in case of need.

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