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Changes of P, Ca, Al and Fe contents in fringe marshes along a pedogenic chronosequence in the Pearl River estuary, South China

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ABSTRACT

Soil and plant samples were collected in four fringe marsh zones (i.e., A, B, C and D zones) along a pedogenic chronosequence in the Pearl River estuary in the Spring of 2009. Samples were subjected to a total digestion technique and analyzed for P, Ca, Al and Fe in order to study the changes of nutrient contents, storages in soils and their bioavailabilities to wetland plants (e.g. *Cyperus malaccensis*) in four zones. Results showed that soil Ca increased with depth along soil profiles, while P, Al and Fe generally kept constant in soil profiles in four zones. Al and Fe contents in the top 10 cm soils showed significant decreases from D to A zone, while a significant increase in Ca contents ($P < 0.05$). Significant increases along pedogenic chronosequence for P, Al and Fe at 30–40 cm soil horizons were also observed. Ca was mainly accumulated in plant aboveground parts; Al and Fe were accumulated in the belowground parts; while P was homogeneously distributed among the tissues of *C. malaccensis*. *C. malaccensis* in D zone had lower Bio-concentration factors (BCFs) of P in the shoots and Al and Fe in the roots, and higher values of Ca in the shoots than those in older zones ($P < 0.05$). Compared to Al and Fe, both Ca and P had relatively higher translocation capacities for *C. malaccensis*, while only lower TFs for P and higher values for Al and Fe in D zone were observed than those in A and B zones ($P < 0.05$). Except for Al with no significant changes, the total BCFs for P and Fe showed an increasing trend with soil ages, while a decreasing trend for Ca. The total bio-storage factors (TBSFs) of P and Ca declined with the pedogenic time, whereas an increase for Fe. The results of this study can contribute to the wetland conservation and management in the Pearl River estuarine region.

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1. Introduction

Coastal reclamation has resulted in a sharp decline in wild plant biomass through direct hewing and reaping, and indirect changes in soil fertility, hydrological connections and micro-organisms activities (Gu et al., 2003). Reclamation should take the dominant responsibility for the decrease in coastal wetlands as the coastal reclamation makes wild tidal wetlands suitable for human use by drainage, diking, dam construction and other anthropogenic disturbances (Iost et al., 2007). It is estimated that coastal wetlands are disappearing by 1% per year globally (Hua and Jia, 1996). There have been increased interests in the changes of ecological processes in the reclaimed marshes to evaluate wetland value loss or the restoration potential. Giani and Landt (2000) and Mueller-Althen (1994) reported the effects of reclamation on soil formation processes in recently reclaimed soils through dewatering, subsidence, desalinization and decalcification. Gu et al. (2003) also addressed that the reclamation retards direct contact between salt

marshes and sea water and results in the changes of wetland ecological characteristics. Recently, Iost et al. (2007) presented that certain chemical properties of reclaimed tidal marsh soils, i.e., electrical conductivity (water), exchangeable sodium percentage, soil organic carbon, pH, carbonate, calcium, magnesium, potassium and phosphorus content, changed greatly due to drainage, diking and dam construction. In addition, coastal reclamation has also been widely reported to cause higher sediment loads, and heavy metal and organic pollution of coastal waters and sediments/soils in estuaries or the aquatic–terrestrial environment (Feng et al., 2004; Gong et al., 2007; Nayar et al., 2003; Cui et al., 2009). However, the availability of sedimentation accumulation caused by coastal reclamation may also produce new fringe salt marshes around the embanked dams after several successive stages (Redfield, 1972). Therefore, understanding the ecological characteristics of the new fringe salt marshes can help to know salt marsh development and formation and can provide valuable information for regional planning and sustainable development. Although marsh geogenesis has been realized artificially by dam construction, pumping of suspended material into the enclosed area and drainage by artificial canals (Giani and Landt, 2000), little information is available on changes in the ecological processes and

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functions of the fringe marshes along pedogenic chronosequence at an estuary with an intense reclamation (lost et al., 2007; Wu et al., 2008).

The Pearl River estuary is typical of a fragile coastal ecosystem, where human activities, especially coastal reclamation on highly erodible intertidal soils, have caused an intensive wetland reduction on degradation or loss since the 1950s (Cui, 2004). During the period from 1978 to 2003, rapid economic growth and urban development in this region have led to a conversion of 5.62×10^4 hm² original tidal marshes to agriculture, housing and industry (Huang and Chen, 2006). Wanqingsha, a reclaimed region located at the northwest of the Pearl River estuary, was an underwater shallow two centuries ago. With the first migration in the 1850s, reclamation started in miniature by manual labor. Large-scale reclamations were organized by the local government since the 1970s. Up to date, a total of 21 embankments have been built and about 5200 hm² of underwater shallows have been converted to arable land through the riprap drainage. The construction of sluices, dams and roads significantly decreased the flow of water intersections and favored sand sedimentation near sluices and embankments, leading to the formation of some small fringe marshes (Ehrenfeld, 2000). These small fringe marshes, primarily dominated by *C. malaccensis* at the inter-tidal zones undergoing tides twice a day, are sensitive to the changes in hydrological conditions and the 'nutrient stream' from irrigation channels. Therefore, studies on changes of mineral elements related to pedogenesis in the newly-generated fringe marshes are critically important for understanding the impacts of pedogenesis time on biogeochemical processes in estuary/coastal wetlands.

The primary objective of this study was: (1) to investigate how four mineral elements (P, Al, Ca and Fe) vary in soils, overlying water and plants from the fringe marshes formed during four different periods; (2) to determine wetland plant's capabilities of accumulation and translocation and assess the bioavailability of the above elements using total bio-concentration factor (TBCF) and bio-storage factor (TBSF) along pedogenic chronosequence.

2. Materials and methods

2.1. Study area

The study area is located in the north of the Pearl River estuary, Guangdong Province, South China (22°36'39"–22°44'36"N and 113°23'42"–113°38'34"E). It covers approximately 2250 hm² and has a subtropical maritime monsoon with annual mean temperature of 23.2 °C and mean annual precipitation of 1655.7 mm. Soil types in this region are primarily paddy soil, red soil, garden soil and coastal salt marsh soil. Wetland plants (e.g. *C. malaccensis*) grew and small fringe marshes generated/developed near the embankments, which were periodically built during different periods (i.e., a century ago, 1978–1988, 1988–1992 and 1992–1995). Correspondingly, these locations with different reclamation histories were named A, B, C and D zones, respectively (Fig. 1). The dominant plant cover in these inter-tidal fringe marshes of four zones is *C. malaccensis*.

2.2. Sample collection and analysis

Four sampling sites were randomly selected in each zone and soil samples collected from four sites were regarded as four replicates for each zone (Fig. 1). Soil cores from 0 to 60 cm depth were collected using a soil auger (4.8-cm diameter) at each sampling site in the spring (March–April) of 2009, and sectioned into 0–10, 10–20, 20–30, 30–40, 40–50 and 50–60 cm horizons to investigate the variability of soil nutrients in the vertical

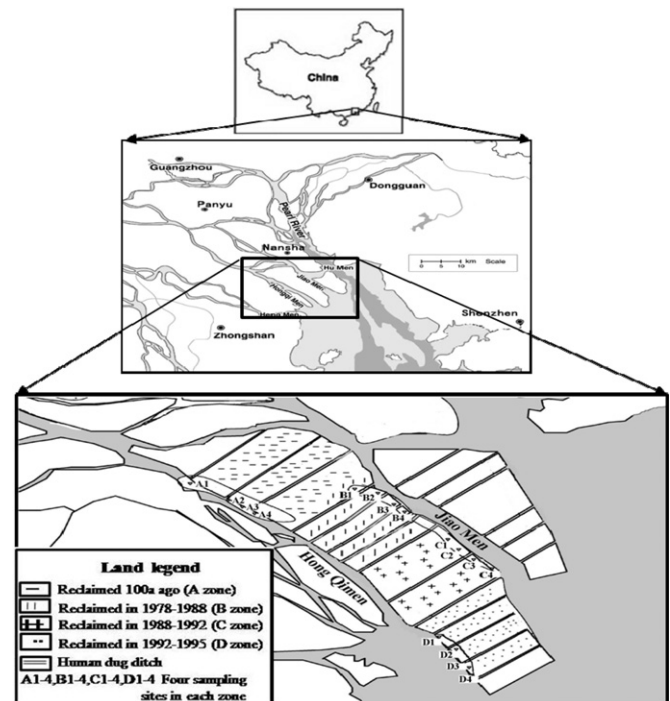


Fig. 1. Locations of the sampling sites in the fringe marshes of the Pearl River Estuary.

direction. A total of 96 soil samples were collected in this study. Three single 4.8-cm diameter soil cores were collected from each soil horizon, oven-dried at 105 °C for 24 h, and weighed for bulk density and moisture content determination. Measures were taken to avoid introducing other contaminants at each site, such as dumpsite garbage, wastewater effluents or compost. All soil samples were air dried at room temperature and sieved through a 2-mm nylon sieve to remove coarse debris. All the air-dried soil samples were then ground with a pestle and mortar until all particles passed a 0.149-mm nylon sieve.

The overlying water samples were collected in plastic bottles, which had been previously soaked in 10% nitric acid for 48 h and thoroughly rinsed with deionized-distilled water. Water samples were taken at each sampling site when soil samples were collected and then stored in a refrigerated chamber. A total of sixteen water samples were brought to the laboratory for chemical analysis. During sample collection, both pH and salinity were measured using a Hach pH meter (Hach Company, Loveland, CO, USA) and a VWR Scientific conductivity meter (VWR Scientific, West Chester, Pennsylvania, USA), respectively.

Plant quadrats (1 m × 1 m) with 3 or 4 replicates were investigated and plant height, density and coverage were also recorded at each soil sampling site. Aboveground biomass (AGB) samples were taken by harvesting the aboveground plant material from each quadrat, washed and then oven-dried for 72 h at 60 °C to constant weight. Belowground biomass (BGB) was determined by sampling soil columns in steel cylinders (20-cm diameter and 20-cm height), after the soil was washed off, and then same processes described for an AGB were conducted. The entire root system was carefully excavated in the 20 cm soil depth, since most roots of *C. malaccensis* distributed within 0–20 cm soils (Zeng et al., 2009).

For analysis of total contents of aluminum (Al), iron (Fe), calcium (Ca) and phosphorous (P), soil, plant and water samples were digested in an HClO₄–HNO₃–HF mixture (HClO₄:HNO₃:HF=2:1:1) in Teflon tubes at 160 °C for 6 h in an oven. The solution of the digested soil/plant/water samples were analyzed by inductively

coupled plasma atomic absorption spectrometry (ICP/AES). Quality assurance and quality control were assessed using duplicates, method blanks and standard reference materials (GBW07401) from the Chinese Academy of Measurement Sciences, which were applied to each batch of samples (1 blank and 1 standard for each 10 samples). The recoveries of samples spiked with standards ranged 90–104%. Soil organic matter (SOM) was measured using dichromate oxidation (Nelson and Sommers, 1982). Soil organic matter was converted to soil organic carbon (SOC) by timing the Bemmelen index (0.58). The pH values and salinities of soil (soil/water=1:5) and water samples were measured with a pH meter and a salinity meter. Soil salinity expressed as both ‰ and EC_E (electrical conductivity of a vacuum extract). Tables 1 and 2 summarize the selected soil and water properties in this study, respectively.

2.3. Parameters calculation

2.3.1. Soil porosity

$$P = \frac{M}{(100-M)/Bd + M}$$

where P is the calculated porosity of one soil sample, M is the soil moisture and Bd is short for the bulk density (Lozano et al., 1983).

Table 1

Soil chemical and physical properties of the sampling zones.

Zones	Depth (cm)	Porosity	pH _(H₂O)	Salinity (‰)	Bulk density (g cm ⁻³)	EC _E (uS cm ⁻¹)	SOC(g kg ⁻¹)	Moisture (%)
A	0–10	0.45 ± 0.014 ^{a 12}	7.36 ± 0.23 ^{a 1}	0.1 ± 0.05 ^{a 12}	1.12 ± 0.015 ^{a 1}	367 ± 11 ^{a 1}	14.7 ± 0.46 ^{a 1}	41.92 ± 0.45 ^{a 1}
	10–20	0.46 ± 0.017 ^{a 1}	7.62 ± 0.18 ^{a 1}	0.2 ± 0.07 ^{a 1}	1.00 ± 0.044 ^{a 2}	381 ± 27 ^{a 1}	13.5 ± 0.34 ^{a 2}	45.84 ± 0.64 ^{a 2}
	20–30	0.43 ± 0.010 ^{ab 2}	7.94 ± 0.12 ^{a 2}	0.1 ± 0.02 ^{a 2}	1.12 ± 0.033 ^{a 1}	379 ± 21 ^{a 1}	14.0 ± 0.32 ^{a 12}	40.42 ± 0.77 ^{a 3}
	30–40	0.48 ± 0.019 ^{a 1}	7.96 ± 0.18 ^{a 2}	0.2 ± 0.03 ^{a 1}	1.00 ± 0.029 ^{a 2}	385 ± 9 ^{a 1}	18.8 ± 0.70 ^{a 3}	47.76 ± 0.57 ^{a 4}
	40–50	0.44 ± 0.031 ^{a 12}	8.08 ± 0.23 ^{a 2}	0.1 ± 0.02 ^{a 12}	1.13 ± 0.040 ^{a 1}	323 ± 14 ^{a 2}	13.6 ± 0.33 ^{a 2}	40.93 ± 0.86 ^{a 13}
	50–60	0.45 ± 0.011 ^{a 12}	7.92 ± 0.21 ^{a 2}	0.1 ± 0.08 ^{a 12}	1.00 ± 0.050 ^{a 2}	371 ± 18 ^{a 1}	15.0 ± 0.29 ^{a 1}	45.03 ± 0.10 ^{a 5}
B	0–10	0.46 ± 0.019 ^{a 12}	7.63 ± 0.22 ^{a 12}	0.5 ± 0.03 ^{b 1}	1.20 ± 0.023 ^{b 1}	989 ± 41 ^{b 1}	14.5 ± 0.45 ^{a 1}	41.60 ± 0.71 ^{a 1}
	10–20	0.48 ± 0.024 ^{a 1}	7.95 ± 0.17 ^{b 1}	0.4 ± 0.07 ^{b 1}	1.04 ± 0.035 ^{a 2}	989 ± 28 ^{b 1}	18.0 ± 0.31 ^{b 2}	46.86 ± 0.66 ^{a 2}
	20–30	0.46 ± 0.020 ^{ab 12}	7.66 ± 0.11 ^{b 2}	0.7 ± 0.02 ^{b 2}	1.06 ± 0.050 ^{a 23}	1399 ± 47 ^{b 2}	15.4 ± 0.66 ^{b 1}	44.56 ± 0.90 ^{b 3}
	30–40	0.44 ± 0.012 ^{b 2}	7.81 ± 0.23 ^{a 12}	0.5 ± 0.06 ^{b 13}	1.12 ± 0.031 ^{b 3}	1068 ± 20 ^{b 3}	12.7 ± 0.34 ^{b 3}	41.48 ± 0.87 ^{b 1}
	40–50	0.43 ± 0.022 ^{a 2}	7.88 ± 0.17 ^{a 12}	0.6 ± 0.05 ^{b 34}	1.15 ± 0.054 ^{a 134}	1235 ± 51 ^{b 4}	14.5 ± 0.41 ^{b 1}	40.03 ± 1.08 ^{a 14}
	50–60	0.43 ± 0.016 ^{a 2}	7.71 ± 0.23 ^{a 12}	0.6 ± 0.02 ^{b 4}	1.21 ± 0.060 ^{b 14}	1231 ± 26 ^{b 4}	11.2 ± 0.31 ^{b 4}	38.81 ± 0.43 ^{b 4}
C	0–10	0.53 ± 0.024 ^{b 1}	7.79 ± 0.20 ^{ab 1}	0.5 ± 0.04 ^{b 1}	0.73 ± 0.030 ^{c 1}	1099 ± 56 ^{c 1}	14.6 ± 0.22 ^{a 1}	61.17 ± 1.35 ^{b 1}
	10–20	0.50 ± 0.022 ^{b 1}	7.83 ± 0.19 ^{ab 1}	0.4 ± 0.03 ^{b 2}	0.80 ± 0.019 ^{b 2}	970 ± 44 ^{b 2}	15.2 ± 0.43 ^{c 1}	55.64 ± 0.82 ^{b 2}
	20–30	0.45 ± 0.017 ^{b 2}	7.84 ± 0.19 ^{ab 1}	0.6 ± 0.07 ^{c 13}	0.75 ± 0.036 ^{b 12}	1239 ± 24 ^{c 3}	14.5 ± 0.65 ^{ab 1}	52.23 ± 1.25 ^{c 2}
	30–40	0.62 ± 0.023 ^{c 3}	7.84 ± 0.25 ^{a 1}	0.6 ± 0.01 ^{b 3}	1.31 ± 0.038 ^{c 3}	1219 ± 41 ^{c 3}	14.6 ± 0.26 ^{c 1}	55.32 ± 2.71 ^{c 2}
	40–50	0.62 ± 0.030 ^{b 3}	7.88 ± 0.17 ^{a 1}	0.4 ± 0.05 ^{c 2}	1.06 ± 0.034 ^{a 4}	980 ± 49 ^{c 2}	14.7 ± 0.43 ^{b 1}	60.87 ± 2.50 ^{b 1}
	50–60	0.68 ± 0.021 ^{b 4}	7.57 ± 0.18 ^{a 1}	0.6 ± 0.03 ^{b 3}	1.10 ± 0.042 ^{a 4}	1239 ± 62 ^{b 3}	14.7 ± 0.31 ^{a 1}	66.34 ± 2.43 ^{c 3}
D	0–10	0.57 ± 0.017 ^{b 1}	8.00 ± 0.11 ^{b 1}	0.3 ± 0.07 ^{c 12}	0.80 ± 0.034 ^{c 1}	704 ± 24 ^{d 1}	16.4 ± 0.40 ^{b 1}	62.68 ± 1.94 ^{b 1}
	10–20	0.45 ± 0.021 ^{a 2}	8.12 ± 0.18 ^{b 1}	0.3 ± 0.01 ^{c 1}	0.84 ± 0.042 ^{b 1}	788 ± 15 ^{c 2}	19.5 ± 0.29 ^{d 2}	49.49 ± 1.23 ^{c 2}
	20–30	0.42 ± 0.010 ^{a 2}	7.95 ± 0.13 ^{a 1}	0.4 ± 0.04 ^{d 2}	0.70 ± 0.018 ^{b 2}	980 ± 25 ^{d 3}	14.5 ± 0.44 ^{ab 3}	51.25 ± 1.75 ^{d 2}
	30–40	0.28 ± 0.014 ^{d 3}	8.01 ± 0.14 ^{a 1}	0.3 ± 0.02 ^{c 1}	0.72 ± 0.036 ^{d 2}	744 ± 34 ^{d 12}	13.4 ± 0.51 ^{b 4}	34.80 ± 1.45 ^{b 3}
	40–50	0.35 ± 0.011 ^{c 4}	8.03 ± 0.09 ^{a 1}	0.4 ± 0.05 ^{c 2}	0.73 ± 0.033 ^{b 2}	822 ± 53 ^{d 2}	12.5 ± 0.23 ^{c 5}	42.78 ± 1.93 ^{c 4}
	50–60	0.24 ± 0.007 ^{c 5}	7.85 ± 0.11 ^{a 1}	0.5 ± 0.01 ^{c 3}	0.62 ± 0.017 ^{c 3}	1095 ± 40 ^{c 4}	11.5 ± 0.47 ^{b 6}	34.06 ± 1.60 ^{d 3}

^{abcd}The different letters represent significant difference ($P < 0.05$) between four sampling zones.

¹²³⁴The different numbers represent significant difference ($P < 0.05$) between different soil horizons of the same sampling zone.

Table 2

Chemical properties of the overlying water in four sampling zones.

Zones	Salinity (‰)	pH	Total concentrations (mg l ⁻¹)			
			Ca	P	Al	Fe
A	0.25 ± 0.04a	6.50 ± 0.11a	46.11 ± 0.53a	0.32 ± 0.004a	0.03 ± 0.002a	0.001 ± 0.000a
B	0.90 ± 0.05b	6.40 ± 0.08a	62.31 ± 3.94b	0.35 ± 0.010b	0.03 ± 0.003a	0.001 ± 0.000a
C	2.50 ± 0.07c	6.23 ± 0.19a	81.48 ± 0.92c	0.65 ± 0.023c	0.04 ± 0.001b	0.000 ± 0.000a
D	0.25 ± 0.01a	6.38 ± 0.16a	46.53 ± 0.71a	0.84 ± 0.032d	0.02 ± 0.001c	0.000 ± 0.000a

^{abc}Different letters represent the significant differences between four sampling zones ($P < 0.05$).

2.3.2. Bio-concentration factor (BCF)

According to Zayed et al. (1998), the bio-concentration factor (BCF) of one element in the plant tissues (roots or shoots) was calculated as follows:

$$BCF = \frac{C_p}{C_s}$$

where C_p is the element concentration in plant tissues at harvest (mg kg⁻¹), C_s is the element concentration in the soil (mg kg⁻¹).

2.3.3. Translocation factor (TF)

The translocation factor (TF) was calculated by dividing the concentration of one element accumulated in the root tissues by that accumulated in the aerial part to evaluate the accumulation capability by plants. TF is given by,

$$TF = \frac{C_a}{C_r}$$

where C_a is the amount of the element accumulated in the aerial part (mg kg⁻¹), C_r is the amount of the element in the root tissues (mg kg⁻¹).

2.3.4. Total bio-concentration factor (TBCF) and total bio-storage factor (TBSF)

The central focus of this study is the average accumulation level of the whole plant, so the average BCF of the shoot and root

are calculated. The average values of soil concentrations and storages in 0–10 and 10–20 cm soil horizons for parameter calculations are adopted, as most roots of *C. malaccensis* distributed in 0–20 cm soil depth. In order to make results more accurate, the biomass of shoot and root and the bulk density of both soil layers are taken into account. The average TBCF was calculated as follows:

$$\begin{aligned} \text{TBCF} &= \frac{\text{(the average concentration of one element in the whole plant)}}{\text{(the average concentration of the element in 0–20 cm soil horizons)}} \\ &= \frac{[(C_{\text{shoot}} \times B_{\text{shoot}} + C_{\text{root}} \times B_{\text{root}}) / (B_{\text{shoot}} + B_{\text{root}})]}{[(C_{0-10} \times Bd_{0-10} + C_{10-20} \times Bd_{10-20}) / (Bd_{0-10} + Bd_{10-20})]} \end{aligned}$$

where C_{shoot} and C_{root} are the element concentrations in shoot and root, respectively, mg kg^{-1} ; B_{shoot} and B_{root} are, respectively, the dry biomass of shoot and root in $1 \text{ m} \times 1 \text{ m}$ quadrat, g m^{-2} ; C_{0-10} and C_{10-20} are, respectively, the element concentration in 0–10 and 10–20 cm soil horizons, mg kg^{-1} dry soil; Bd_{0-10} and Bd_{10-20} are respective the bulk density of 0–10 and 10–20 cm soil horizons, g cm^{-3} .

The bio-storage factor (BSF) is defined to trace the variability of nutrient storages in plant tissue biomass in $1 \text{ m} \times 1 \text{ m}$ quadrat relative to soil storages on the unit ground-area basis down to 0.2 m. The total bio-storage factor (TBSF) of both aboveground and belowground biomasses was calculated as follows:

$$\begin{aligned} \text{TBSF} &= \frac{\text{(the total storage of one element in plants within } 1 \text{ m} \times 1 \text{ m quadrat)}}{\text{(the total soil storage of the element on } 1 \text{ m} \times 1 \text{ m} \times 0.2 \text{ m volume basis)}} \\ &= \frac{[(C_{\text{shoot}} \times B_{\text{shoot}} + C_{\text{root}} \times B_{\text{root}}) \times 1 \text{ m} \times 1 \text{ m}]}{[(C_{0-10} \times Bd_{0-10} + C_{10-20} \times Bd_{10-20}) \times 100 \text{ cm} \times 100 \text{ cm} \times 10 \text{ cm}]} \end{aligned}$$

the symbols represent the same meanings as mentioned above.

2.4. Statistical analysis

Statistical analysis was carried out using SPSS 16.0 (SPSS München, Germany) for Windows. The results were tested for correlation between the content of the respective nutrient and elapsed time after reclamation using the Pearson correlation coefficient based on the assumption that the data was normally distributed. The ANOVA analysis was performed to test the differences between soil horizons and sampling zones. Differences were considered to be significant if $P < 0.05$. Graphs were performed using Suffer 32 7.0 and Origin 6.0 software packages.

3. Results and discussion

3.1. Soil properties in four sampling zones

As shown in Table 1, significant changes were observed in a few soil properties. The soil bulk density greatly varied from 0.62 to 1.31 g cm^{-3} , and they were significantly lower in the D zone than in other zones ($P < 0.05$). The large variations in the average bulk densities of soil cores (0–60 cm) from 0.74 g cm^{-3} in the D zone to 1.06 g cm^{-3} in the A zone occurred along the pedogenic chronosequence. However, the marsh soils of C and D zones generally had significantly higher soil moisture compared to those of A and B zones ($P < 0.05$). Soil porosity showed significantly higher values in the C zone, while lower values in deep layers of D zone than those in A and B zones ($P < 0.05$). This was closely linked to soil compaction, dewatering and subsidence in wetland pedogenesis and development processes (Giani and Landt, 2000).

Soil pH values showed subalkalinization condition in this region and most horizons showed no significant differences

between four sampling zones ($P > 0.05$), whereas they declined from 8.00 to 7.36 in the top 10 cm soil horizon along the increasing chronosequence (from D to A zone), showing the obvious trend of dealcalization in the pedogenesis process. Kumpiene et al. (2008) presented that the alkalescence condition would be more suitable for mineral element mobilization and plant absorption. Contrary to findings that the highest EC_E is associated with more recent marsh soils (Iost et al., 2007), the EC_E in the fringe marshes ranged $323.7\text{--}1399.0 \text{ uS cm}^{-1}$ with the highest value in the B zone, which was generated in relatively earlier years (1978–1988) (Table 1), indicating the highest salinity in B zone but not in D zone. However, the marsh soils of A zone contained much lower salinity or EC_E as did in soils of other zones ($P < 0.05$). SOC contents in both 0–10 and 10–20 cm soil horizons significantly decreased from D to C zone (0–10 cm: $16.4 \rightarrow 14.6 \text{ g kg}^{-1}$; 10–20 cm: $19.5 \rightarrow 15.2 \text{ g kg}^{-1}$; $P < 0.05$), suggested significant SOC lost in the first few years of pedogenesis (Rumpel and Knabner, 2010). The higher SOC in upper soils (0–30 cm) was observed compared to deeper soils (30–60 cm) in B and D zones, suggesting the accumulation of organic matter in surface soils. However, we could observe the higher SOC contents in deeper soils (30–60 cm) than those above 30 cm soil horizons in the A zone, which might be caused by an SOC decomposition during the long-term tillage (Zhang et al., 2007). The salinity and pH of the soils (Table 1) were not consistent with those in the overlying water (Table 2), which was most likely due to differences in composition and structure of sediment, water flow conditions and pollution duration, since these factors can greatly change water/sediment properties (Ferreira et al., 1996).

3.2. Changes of soil nutrients along soil profiles and the pedogenic chronosequence

Fig. 2 shows changes in Ca, P, Al and Fe contents along soil profiles in four sampling zones. Ca contents varied between 1971.08 and $7750.50 \text{ mg kg}^{-1}$, and had higher values in deeper soils than in upper soils ($P < 0.05$) in each sampling zone, except for the B zone (1978–1988) ($P > 0.05$). This could be explained by the fact that the major fraction of soil calcium-exchangeable calcium in the upper soils was most readily leached and absorbed into roots (Lawrence et al., 1997). There were similar distributions of soil Ca at different horizons along the pedogenic chronosequence in despite of no significant differences between four zones ($P > 0.05$). This indicated that longer reclamation history did not show great effects on Ca contents in these marsh soils, due to Ca deposition and supply from tidewater.

Several studies have shown that phosphorus can serve as a useful indicator of pedogenic processes (Lajtha and Schlesinger, 1988). However in this study, no significant differences for total phosphorus (TP) contents were observed between four zones, indicating that combined with the human effects, the natural variation of soil phosphorus along the pedogenic chronosequence cannot be observed. Furthermore, the heavy fertilization of crops over a long period elevated P contents in soils with longer pedogenic age (Iost et al., 2007). Similarly, there were not significant differences between TP contents at different soil horizons in each zone despite that soil P generally showed decreasing trends with depth along soil profiles ($P > 0.05$). It has been certified that P can easily accumulate in the surface soil via surface inflows and leach to deep bulk (Jobbágy and Jackson, 2001; Bai et al., 2007). However, the high soil moisture or the incorporation of plant root in wetlands increased rapidly released P (RRP) in soils (Weaver et al., 1988), which would contribute to P leaching downward and removing from the ecosystem with soil development.

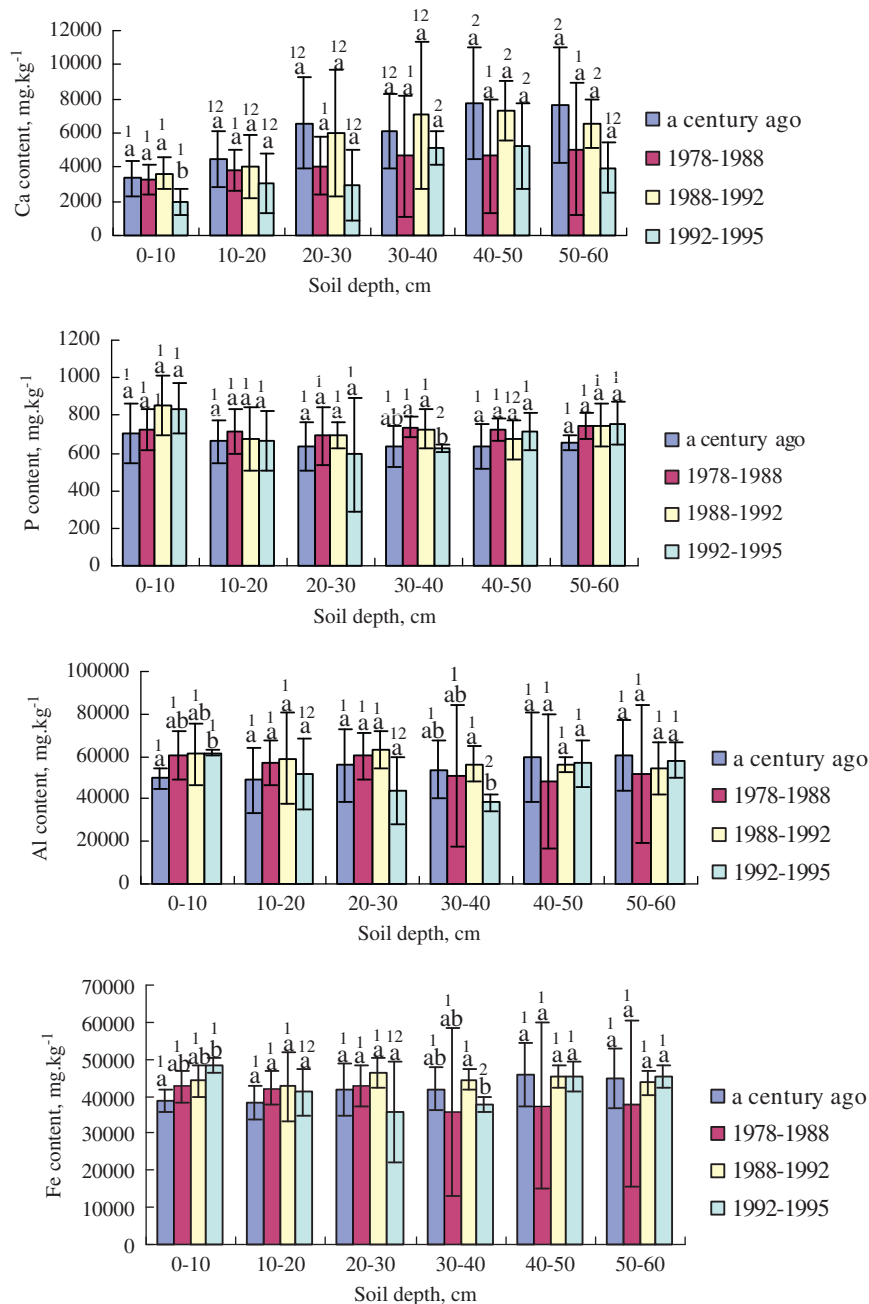


Fig. 2. Total contents of soil Ca, P, Al and Fe in soil profiles from four sampling zones. The different letters represent significant difference ($P < 0.05$) between four sampling zones. The different numbers represent a significant difference ($P < 0.05$) between different soil horizons of the same sampling zone.

Both Al and Fe showed similar profile distributions in each sampling zone (Fig. 2). Correlation analysis showed that there were significantly positive correlations between Al and Fe contents ($r=0.828$, $P < 0.01$). In detail, they kept constant along soil profiles in A, B and C zones ($P > 0.05$), while showed some trend of “increasing after decreasing” in D zone ($P < 0.05$) (Fig. 2). The same distribution patterns of these two metals suggested that the dissolution processes of both Al and Fe from soils were regulated by chelation with certain active components of the SOC passed through the soil profiles (Pohlman and McColl, 1988). However, except the significant decreasing in the top 10 cm soils along chronosequence from D to A zone ($P < 0.05$), there was no apparent decrease in the concentrations of Al and Fe in other horizons with increasing soil ages. This was certainly partially due to the formation and precipitation of insoluble Al and Fe minerals in this subalkaline region, which make Al

and Fe relatively stable compared to Ca and P (Lajtha and Schlesinger, 1988).

As mentioned above, mobilization of Al and Fe was pH dependent (Pellerin et al., 2002; Sims and Patrick, 1978). Correlation analysis showed Al and Fe were both significantly and positively correlated with soil pH values of soil profiles ($r_{(Al)}=0.813$; $r_{(Fe)}=0.835$, $P < 0.05$). Therefore, higher soil pH values (Table 1) in the top 10 cm soils of the D zone could result in a decrease in the solubility of Al and Fe compared to the A zone. Additionally, the lower Al and Fe contents in the top soils of the A zone also suggested the scour effect of fresh water with lower salinity (Table 2) flowing through this zone favored mineral elements (i.e., Al and Fe) leaching to lower reaches and deeper horizons (Moalla et al., 1998). Soil properties such as porosity, bulk density and moisture had great effects on leaching of Al and Fe. The higher bulk density, and lower porosity and soil moisture

contributed to the enrichment of Al and Fe in the top soils of B zone compared to C and D zones. However, the higher salinity of sea water in the C zone (Table 2) intensified the deposition of Al and Fe from an overlying water to the marsh soils (Johnson et al., 1999). Significant enrichments of Al and Fe in the top 10 cm soils of the D zone were mostly because higher soil organic matter in upper soils and smaller porosity of deeper soils (such as below 30 cm) retarded Al and Fe leaching downward (Xue and Liao, 2004; Chuan et al., 1996).

Correlation analysis showed no significant correlations between Ca, Al, Fe and P in A, B and C zones, while soil P was significantly correlated with Al ($P < 0.05$) and Fe ($P < 0.01$) in D zone (data not shown). This might be because residual- and organic-P were the dominant forms in the relatively mature soils of older zone, while the dominant forms were Al- and Fe-P in the newly-generated near shore sediments of younger zone (Noll et al., 2009).

3.3. Accumulation and translocation of P, Ca, Al and Fe in *C. malaccensis*

Biological concentration factor (BCF) and translocation factor (TF) have been widely used in soil nutrient cycling (Wang et al., 2009). BCF is defined as the ratio of element content in plant tissues (i.e., shoots and roots) to that in their rooted soils. TF is defined as the ratio of one element content in plant shoots to that in plant roots. The BCFs and TFs of P, Ca, Al and Fe in *C. malaccensis* are listed in Table 3.

The average BCFs of P had the order of plant shoots > plant roots in both A and B zones, whereas plant roots > plant shoots in C and D zones. However, no significant difference ($P > 0.05$) between BCFs of P in the shoots and roots was found due to the mobility of phosphate. The average BCFs of Ca in four zones followed the order plant shoots > plant roots, while it is an opposite order for the average BCFs of Al and Fe. This indicated that soil Ca trended to concentrate in the leaves, while soil Al and Fe were more likely concentrated in plant roots, and soil P was equivalently distributed in *C. malaccensis*. *C. malaccensis* in D zone had lower BCFs of P in the shoots and those of Al and Fe in the roots ($P < 0.05$), and higher values of Ca in the shoots, but no significant differences for BCFs in the shoots or roots between four sampling zones along the chronosequence were observed ($P > 0.05$, Table 3). This verified that the distribution regime of nutrients in plant tissues of the same species would not change with the soil age to some degree (Mo and Wu, 1988). Generally, the BCFs of Al and Fe in plant shoots and roots were far less than 1, while those of P and Ca were mostly more than 1 in four zones, which indicated that soil P and Ca had higher bioavailability than Al and Fe to *C. malaccensis* (Wang et al., 2009).

With the exception of the lower average TFs of soil P and higher average TFs of soil Al and Fe in younger zones ($P < 0.05$), no significant increasing or decreasing trend for plant element TFs was observed along chronosequence of pedogenesis (Table 3). This indicated that the translocation of the elements from plant roots to shoots remained equilibrium and this equilibrium could not be easily modified by the soil age. However, the average TF of Fe in the shoots (20.62%) of *C. malaccensis* in this study was much lower than that (66.78%) of wheat reported by Bose and Bhattacharyya (2008). This might be due to the extremely higher Fe-loading in those sludge-amended soils than natural marsh soils in this study. Moreover the TFs of all four elements followed the order $Ca > P > Al > Fe$ in four sampling zones, which indicated the higher translocation capacity of Ca and P from the roots to shoots in *C. malaccensis* compared to Al and Fe.

Table 3
Bio-concentration factors (BCFs) of P, Ca, Al and Fe in shoot and root and translocation factors (TFs) of P, Ca, Al and Fe from root to shoot of *Cyperus malaccensis*.

Zone	P		Ca		Al		Fe					
	BCF		BCF		BCF		BCF					
	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root				
A	3.05 ± 0.36a 1	2.76 ± 0.87a 1	1.10 ± 0.09a	1.69 ± 0.26a 1	0.87 ± 0.32a 2	1.95 ± 0.88a	0.03 ± 0.02a 1	0.07 ± 0.03ab 1	0.41 ± 0.16a	0.02 ± 0.01a 1	0.14 ± 0.04a 2	0.16 ± 0.06a
B	3.70 ± 0.43a 1	2.62 ± 0.86a 1	1.41 ± 0.42a	1.59 ± 0.20a 1	0.87 ± 0.20a 2	1.83 ± 0.20a	0.03 ± 0.01a 1	0.11 ± 0.03a 2	0.24 ± 0.04a	0.03 ± 0.01a 1	0.18 ± 0.07a 2	0.14 ± 0.03a
C	2.36 ± 0.34ab 1	3.06 ± 0.81a 1	0.77 ± 0.12b	1.20 ± 0.44a 1	0.84 ± 0.56a 1	1.43 ± 0.51a	0.03 ± 0.01a 1	0.08 ± 0.03ab 2	0.38 ± 0.24a	0.03 ± 0.01a 1	0.14 ± 0.07a 2	0.20 ± 0.15ab
D	2.02 ± 0.44b 1	2.16 ± 0.45a 1	0.94 ± 0.01c	2.38 ± 0.42b 1	1.18 ± 0.50a 2	2.24 ± 0.81a	0.03 ± 0.00a 1	0.04 ± 0.01b 1	0.86 ± 0.16b	0.02 ± 0.00a 1	0.07 ± 0.03b 2	0.34 ± 0.09b

BCF = [element concentration in plant tissue] / [average concentration of element in 0–20 cm soil].

TF = [element concentration in shoot] / [element concentration in root].

a, b, c Different letters represent significant differences between four sampling zones ($P < 0.05$).

1, 2 Different numbers represent significant differences between shoots and roots ($P < 0.05$).

3.4. Bioavailability assessment of soil nutrients using total bio-concentration factor (TBCF) and bio-storage factor (TBSF) along pedogenic chronosequence

The total bio-concentration factor (TBCF, the ratio of the average concentration of one element in the whole plant to that the concentration of the element in the 0–20 cm soil) and the total bio-storage factor (TBSF, the ratio of the total storage of one element in plants in 1 m × 1 m quadrat to the total soil storage on the unit ground-area up to 0.2 m depth) were calculated to contrast bio-availability of soil nutrients to the same species at different development stages (Fig. 3). A higher TBCF was widely used to imply soil having a better bio-availability of nutrients for plant accumulation (Kumar et al., 2010), while the TBSF defined in this study can supply an access to evaluate the overall level of bio-availability and soil ability of nutrient store within a given area. Since plant roots occupy a volume of soil rather than a mass of soil (Johnston et al., 2001), TBSF incorporating biomass and bulk density into the value of areal/volume storage results in a more comprehensive description of the ability of soil volume to store total mass of nutrients and transform to biomass fractions (DeBusk et al., 1994).

The TBCFs of P varied between 2.08 and 3.11 and showed an increasing trend with soil ages ($R^2=0.605$). A potential of *C. malaccensis* to bio-concentrate P is evidently higher compared to another three elements (e.g. Ca, Al and Fe). However, the TBSFs of P decreased from 0.015 in the D zone to 0.011 in the A zone, indicating plant-P storage declined 0.4% relative to soil-P storage within one hundred years ($R^2=0.961$). These findings imply the soil with longer pedogenesis had higher efficiency of both total-P store and available-P supply. The opposite changing of TBCFs and TBSFs reflected the variabilities of ecological factors, such as biomass of plant communities and bulk density of soils, had greatly affected the P distribution patterns in the plant–soil system (Daroub et al., 2010).

Calcium carbonate accumulation was regarded as one of the dominant soil processes (Hobson and Dahlgren, 1998) and decalcification was found in recently reclaimed soils (Mueller-Althen, 1994; Giani and Landt, 2000). In this study, we observed the accumulation of Ca in the top soils of the D zone was significantly lower than those in older zones (e.g. A, B and C zones) (Fig. 2). However, the TBCFs of Ca sharply declined from a maximum of 1.79 in the D zone to a minimum of 1.02 in the C zone after 3–7 years of soil development. Also, the TBSFs of Ca decreased from 0.0081 in the D zone to 0.0039 in the A zone ($R^2=0.741$) (Fig. 3). This indicated pedogenic calcium carbonate from parent materials combined with biogenic particles of calcium carbonate accumulated in soils after the invasion of fringe marshes by *C. malaccensis* extend to Ca mineral pools in wetlands though the available-Ca accumulation seemed to be far less than total-Ca accumulation (Jobbágy and Jackson, 2004).

At pedogenic time scales, the imprint of plants seemed to extend the bio-availability of Fe for root uptake in soils (TBCF and TBSF both increased from D to A zone, $R^2=0.438$ and 0.459, Fig. 3), though the significant increase in BCFs of Fe in plant tissues was only detectable in the roots (Table 3). This suggested that more and more mineral Fe from soils was transformed to biomass Fe and stored in plants with an increased soil weathering, which was apparent with biomass Fe comprising 0.029% of the total Fe in D zone soils, while 0.037%, 0.047% and 0.039% in C, B and A zones, respectively (Fig. 3, TBSFs of Fe). A slightly higher accumulation of Al by plants in older zones also showed the increasing trend of an Al bio-availability with soil pedogenesis. However, little variations ($R^2=0.014$) in TBSFs of Al indicated less changes in relative storages of an Al between soils and plants along pedogenic chronosequence in this study, which clarified an Al was more stable in soils compared to P, Ca and Fe and affirmed the use of aluminum to normalize heavy metals data in pollution assessment studies (Jenne et al., 1980; Bai et al., 2011).

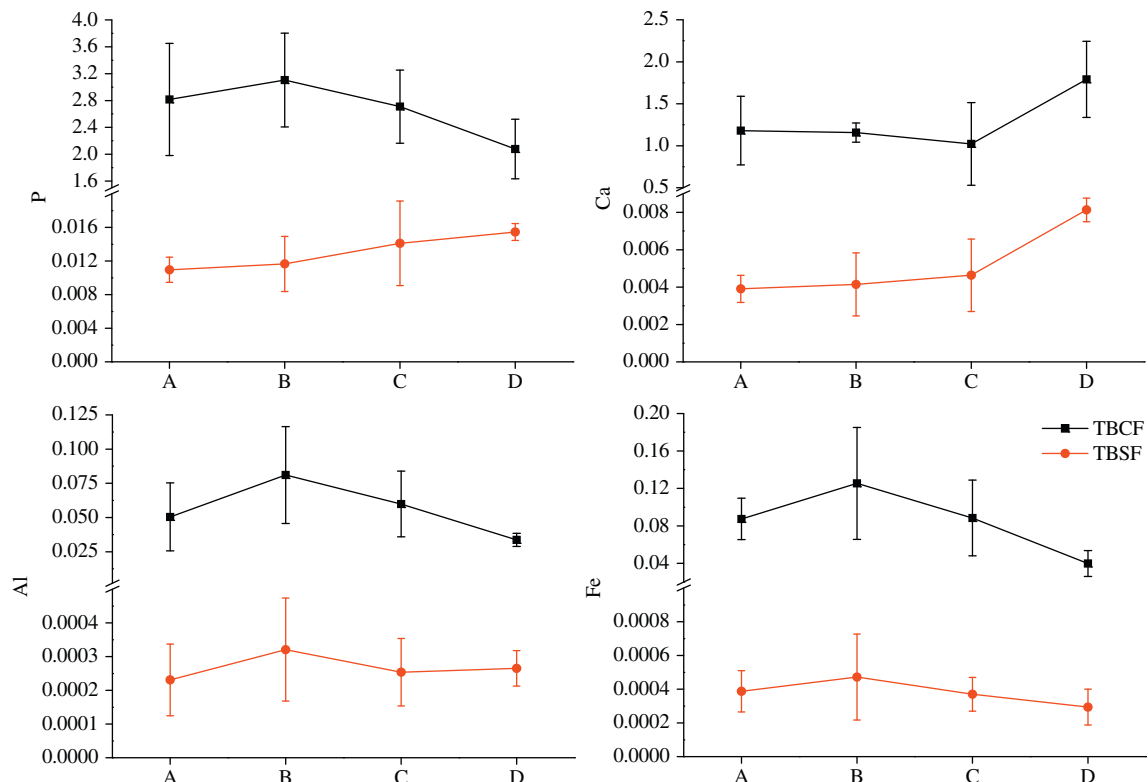


Fig. 3. Total bio-concentration factors (TBCFs) and bio-storage factors (TBSFs) of P, Ca, Al and Fe along pedogenic chronosequence by *Cyperus malaccensis*.

4. Conclusions

The concentrations and storages of four most common elements (P, Ca, Al and Fe) in soil, plant and overlying water along a pedogenic chronosequence were well suited to determine the translocation and transformation of nutrient and/or mineral elements that can be potentially modified by different mechanisms in soil development procedures. The newly-formed fringe marshes showed significantly lower soil bulk density and higher soil moisture compared those well-developed marshes with longer reclamation history. The contents of four elements in soils from four zones showed an increase in Ca and a decrease in Al and Fe in the top soils along the pedogenic chronosequence, while P kept constant in the top soils from the four zones. Except that Ca increased with depth along soil profiles in four zones, another three elements nearly kept constant along soil profiles. As a rule, a higher soil P, Al and Fe accumulation potential by plant roots can be expected in fringe marshes to undergo decades of natural pedogenesis with growing impacts from human activities. The increased average concentrations of P, Al and Fe in the whole plants relative to those in soils indicated the soil with longer pedogenesis contributed to an available nutrient supply. The declined average storages of P and Ca in plants relative to those in soils indicated the speed of deposition exceeded that of uplift/uptake with soil development, and this seems to extend soil P and Ca mineral pools in wetland ecosystems. Although more and more mineral Al and Fe from soils could be transformed to biomass Al and Fe with soil pedogenesis, the insignificant variations of Fe and Al hampered them to be the useful indicators of pedogenic processes as P and Ca.

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