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Long-term changes in topsoil chemical properties under centuries of cultivation after reclamation of coastal wetlands in the Yangtze Estuary, China

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ABSTRACT

Dynamics of reclaimed coastal wetland soils under cultivation has not been well understood, especially at temporal scales longer than a century. In this study, we analyzed major chemical properties of plow-layer soils extensively sampled under two cropping systems (paddy rice vs. upland cropping) along a 500-year soil chronosequence created by intermittent reclamation of coastal salt marshes. The results suggested a rapid desalinization of soil immediately after reclamation. During 500 years of cultivation, the decalcification process lowered soil pH from >8 to nearly neutral. Soil organic carbon (SOC) contents markedly declined in the initial 16 years, but then rapidly recovered within 30 years and thereafter slowly accumulated with cultivation duration. Meanwhile, the recalcitrance of SOC increased. Soil nutrient status was enhanced after centuries of cultivation as indicated by the improved total nitrogen (TN) and phosphorous (TP). Amorphous Fe oxyhydrates progressively decreased, but the crystallinity of Fe oxyhydrates increased with cultivation time. Cropping system greatly affected plow-layer soil properties, with paddy soils having higher SOC, MBC, NH_4OAc-extractable Ca^{2+}, but lower TP, NH_4OAc-extractable K^+, potentially mineralizable nitrogen and Fe crystallinity than upland soils. Most soil properties revealed clear temporal patterns with more remarkable changes occurring in the first several decades after reclamation than in the following centuries. In conclusion, there was a transition phase of the soil system within the first several decades after reclamation of coastal wetlands, possibly harmful to agricultural production, but centuries of cultivation seemed to have significantly improved overall soil fertility.

1. Introduction

Worldwide, there has been a long history for people living in the coastal area to convert wetlands into agricultural lands (Ellis and Atherton, 2003; Healy and Hickey, 2002; Wolff, 1992). In some parts of the world, reclamation of coastal wetlands began thousands of years ago (An et al., 2007; Wolff, 1992). This tradition has not stopped in China, where the area of natural coastal wetlands has shrunk by 51.2% since 1949, primarily due to reclamation for agricultural purposes (An et al., 2007). This gave rise to 1.19×10^6 ha new lands between the 1950s and 1980s (He and Zhang, 2001). Sustainable management of the vast reclaimed lands along shorelines of China and other countries, which should be at diverse stages of development, calls for an understanding of soil dynamics under influences of various agricultural land uses.

There have been investigations on short-term soil dynamics after reclamation of coastal wetland (e.g. Iost et al., 2007; Portnoy, 1999; Santín et al., 2009), but few have addressed how reclaimed soils would change under long-term agricultural activities, especially at a time scale of centuries.

Chronosequence is a very useful, if not the only, tool to investigate soil dynamics at long time scales because it allows for a space-for-time approach (Huggett, 1998). Investigations using this approach, although relatively well conducted under natural conditions (e.g. Hedin et al., 2003; Turner et al., 2007; Walker and Syers, 1976), have been limited for agricultural soils (deMoraesSá and Lal, 2009; deMoraesSá et al., 2009; Zhang and Gong, 2003), greatly restricting our knowledge of soil dynamics in a human-dominated world. Recently, however, the series investigations on a 2000-year cultivation chronosequence in Zhejiang Province, China revealed clear temporal trends in soil physical, chemical and microbiological properties at a millennia scale (Bannert et al., 2011; Cao, 2008; Cheng et al., 2009; Hu et al., 2008; Zou et al., 2011). These explorative studies implied that possible variations of agricultural activities in time or space, which should be roughly comparable in a certain area, were not strong enough to

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obscure overall patterns of soil dynamics at long time scales. With no doubt, information provided by such chronosequence studies was difficult to acquire by other approaches and would be valuable to the understanding of long-term evolution of coastal agricultural soils.

The Chongming Island is the largest estuarine island in China. Half of its present area was obtained by reclamation of wetlands, i.e. salt marshes (He and Gu, 2003). While early reclamation was intermittently performed by local landlords or farmers, modern reclamation has become as frequent as nearly once every 2–3 years due to increasing agricultural demands since the 1950s. Therefore, ideal chronosequences of soils at different developmental stages after wetland reclamation could be identified on the island. Soils there are all derived from the Yangtze River sediments that are dominated by hydromica minerals (He, 1992) and have been developing under similar ecological conditions. Information of the time of wetland reclamation is available in the Chongming County Annals (Zhou and Ji, 1989) or in published works (Gao and Zhao, 2006). Cultivation rarely stopped in reclaimed soils, and agricultural customs were comparable across the island. In addition, soils have relatively young ages as the oldest soils existent in the island are only about 500 years old after being reclaimed (Zhou and Ji, 1989). All those provided good opportunities for studying long-term dynamics of cultivated soils derived from previous estuarine wetlands.

In this study, we identified a 500-year soil chronosequence on the Chongming Island to study how the properties and fertility of reclaimed wetland soils had varied during centuries of cultivation. A variety of chemical parameters were measured for the topsoil under two cropping systems (paddy rice vs. upland cropping). At such a long time scale, it was impossible to control factors such as the land use history and agricultural management practices. Nevertheless, previous studies (Bannert et al., 2011; Cao, 2008; Cheng et al., 2009; Hu et al., 2008; Zou et al., 2011) suggested that in the long term, stochastic variations in these factors would not fundamentally affect the direction of soil changes, and some temporal patterns of soil dynamics could still be expected. Our objectives were to: (1) reveal main changes in topsoil chemical characteristics with cultivation time and (2) understand the effects of cropping systems (paddy rice vs. upland cropping) on soil dynamics.

2. Materials and methods

2.1. Study sites

The Chongming Island is the largest estuarine island in China with a total area of 1267 km^2 (Song, 2009). With a typical north-subtropical monsoon climate, the island has a mean annual temperature of 15.3 °C and precipitation of 1003.7 mm (during 1958–1984). The topography is rather flat and the altitude ranges from 3.2 to 4.2 m. The groundwater table is 85.7 cm on average. Soil substrates all originated from sediments deposited in the Yangtze Estuary. Soil mineralogy is dominated by hydromica with minor proportions of kaoline, chlorite and vermiculite (He, 1992).

A soil chronosequence spanning about 500 years was identified in this study (Fig. 1a), including natural coastal wetlands (i.e. salt marshes) and soils that have been reclaimed and cultivated for 8, 16, 40, 75, 120, 300 and 500 years (referred to as soil ages hereafter). Soil ages were determined according to dikes built at the time of reclamation, historical records and information provided by local inhabitants. Ages of the 8-, 16- and 40-year soils have been reported in the literature (Gao and Zhao, 2006). Ages of the 300- and 500-year soils were inferred from the time when they were inhabited, which was recorded in the Chongming County Annals (Zhou and Ji, 1989). However, ages of the 75- and 120-year soils were determined after consulting at least 5 old local inhabitants and might have uncertainties of ±10–20 years.

Soils of the salt marshes were sampled under *Phragmites australis* communities in the high-tide zone. Cropland soils were sampled from paddy rice and upland fields at the same time. There was a rotation between rice cultivation and dry farming in paddy fields, or purely dry farming rotating between different vegetables in upland fields (Table 1). In the paddy fields, stubbles 15–30 cm high were generally left in the fields after harvesting, and hence about 2.35 t ha^{-1} stubble was annually returned to soil. There was almost no intentional return of crop residues in the uplands fields. Pesticides such as methamidophos, dimehypo, dichlorovos and imidacloprid were regularly applied in both paddy and upland fields. Local farmers rarely used organic fertilizers in recent years. Chemical fertilizers have been applied at a rate of about 400 kg ha^{-1}, of which N:P:K was estimated to be 1:0.33:0.09 (Li, 2006).

2.2. Field sampling

Plow-layer soils were sampled during March–April 2009, when the paddy rice fields had been drained and entered the dry farming period. To account for the effects of factors other than time on soil properties, samples for a single soil age were obtained from 3 to 4 replicate sampling sites under paddy rice and upland cropping, respectively (Fig. 1a). The field sampling strategy is shown in Fig. 1b. At each site, three individual paddy/upland croplands 500–1000 m apart were selected. We tried to select croplands undergoing regular agricultural practices typical of the Chongming Island, which ensured that soils across the chronosequence were under similar land management. Basic soil information has been listed in Table 1. To study the effect of cropping system on soil properties, it would be optimal to find paddy and upland croplands that were not only closely adjacent to each other but also had persisted for as long time as possible. However, such sampling sites were almost impossible to find. Considering that cultivation time influenced dynamics of soils more than their locations, we preferentially chose spatially separated old croplands (i.e. paddy and upland fields) instead of adjacent younger ones. For the salt marsh soils, we sampled at four sampling sites, each with three mosaics of *P. australis* communities 500–1000 m apart.

From individual croplands or *P. australis* communities, six soil cores at the depth of 0–8 cm (i.e. the upper part of plow layer, which was more influenced by agricultural activities than the lower part) were collected using self-made steel corers (4.3 cm in diameter) along a diagonal transect. Field-moist soils were then homogenized by passing through an 8-mm sieve, handpicked to remove litters or stones and composited by sampling site. This produced 3 or 4 composite samples for each cropping system (or the marshes) at each soil age. Part of the composite samples was stored at 4 °C and the rest was air-dried.

2.3. Soil analysis

Soil salinity was measured with a platinum electrode on soil slurries at 5:1 water:soil ratio following Lu (1999) and expressed as the percentage of total water soluble salts on a dry weight base. Soil pH was measured on soil slurries at 2.5:1 water:soil ratio using a glass electrode. Carbonate content was determined by back-titrating soils neutralized with excess 1 M HCl. Soil texture was analyzed with a LS 230 laser particle size analyzer (Beckman, USA). Na^+, K^+, Ca^{2+} and Mg^{2+} were extracted with 1 M NH_4OAc at pH 7.0. Free Fe oxyhydrates (Fe_d) were extracted with citrate–dithionite–bicarbonate (DCB), and amorphous Fe oxyhydrates (Fe_o) with oxalic acid–ammonium oxalate (Lu, 1999). The extracted Na, K, Ca, Mg and Fe were then measured with an inductively coupled

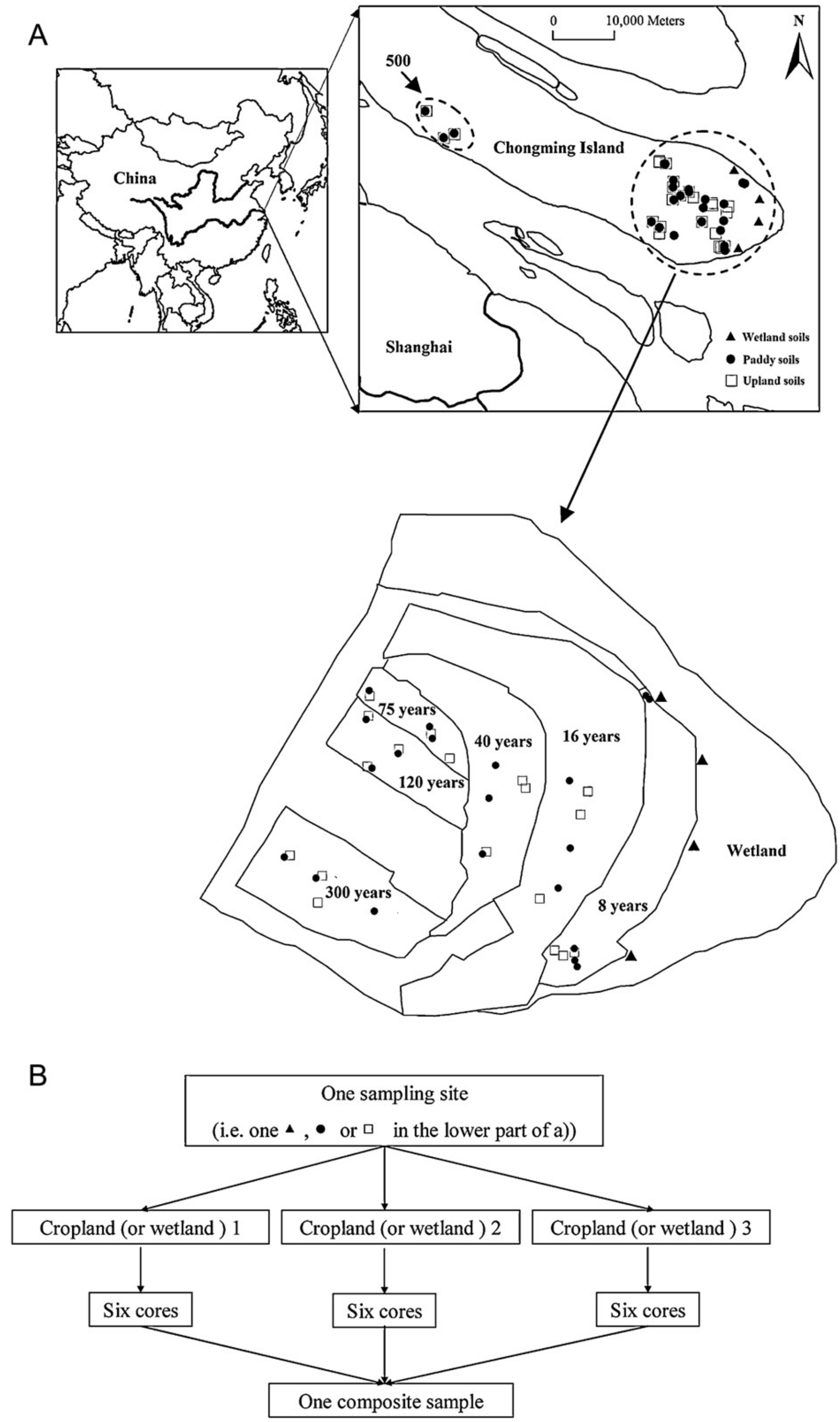

Fig. 1. Map of sampling sites (a) and field sampling strategy at each sampling site (b). Sampling site with soil ages ≤ 300 years were amplified in the lower part of (a), where the spatial ranges and soil ages were labeled in each chronosequential area. Wetlands referred to the salt marshes.

plasma (ICP) spectrometer (P4010, Hitachi, Japan). Soil organic carbon (SOC) was measured with a TOC analyzer (HT1300, Analytikjena, Germany) after removing soil carbonates with 1 M HCl. Labile carbon (LC) was estimated as the SOC fraction oxidizable by 333 mmol $KMnO_4$ after Blair et al. (1995). Potentially mineralizable carbon (PMC) was determined by a 28-d incubation of 45 g field moist soils at 25 °C (Wright et al., 2004). Soils were placed in a 50-ml beaker together with a plastic vial containing 20 ml of 1 M NaOH, and the amount of CO_2-C trapped in NaOH (i.e. PMC) was quantified by titration with 0.5 M HCl after precipitation of Na_2CO_3 with $BaCl_2$. Potential mineralizable nitrogen (PMN) was determined as changes in the sum of NH_4^+ and NO_3^- after incubating soils at 25 °C for 28 d (Wright et al., 2004). Soil microbial biomass carbon (MBC) was determined by the $CHCl_3$

Table 1
Some basic characteristics of soils along the chronosequence.[a]

Soil age (year)	Land use	Tillage years[b]	Dominant cover plants	Soil taxonomy[c]	Clay (%)[d]	Silt (%)[d]	TN (g kg^{-1})[d]	Ti/Zr[d]
0	Wetland	0	*Phragmites australis*	Solonchaks	13.25 ± 1.84 ab D	76.25 ± 0.24 cd D	1.11 ± 0.2 ab BC	61.99 aA
8	Paddy	6	Rice, wheat	Fluvisols	11.75 ± 1.75 ab	67.04 ± 2.86 ab	0.9 ± 0.07 ab	63.19 a
	Upland	6	Cauliflower, watermelon, maize, etc.	Fluvisols	9.72 ± 0.76 ABC	69.93 ± 1.72 ABC	0.93 ± 0.06 AB	71.08 aA
16	Paddy	14	Rice, wheat	Fluvisols	8.79 ± 0.94 a	69.9 ± 3.09 abcd	0.59 ± 0.09 a	53.86 a
	Upland	>10	Cauliflower, rape, pakchoi, etc.	Fluvisols	6.49 ± 0.22 A	54.5 ± 2.05 A	0.67 ± 0.07 A	67.51 aA
40	Paddy	38	Rice, barley/wheat	Fluvisols	10.83 ± 0.48 ab	66.6 ± 2.15 ab	2.12 ± 0.04 b	75.44 a
	Upland	>30	Cauliflower, rape, pakchoi, etc.	Fluvisols	8.95 ± 0.4 AB	69.7 ± 0.78 AB	1.63 ± 0.09 DE	68.41 aA
75	Paddy	>50	Rice, wheat/rape	Fluvisols	11.17 ± 0.13 ab	67.83 ± 0.32 abc	1.24 ± 0.26 ab	63.54 a
	Upland	>50	Cauliflower, rape, pakchoi, etc.	Fluvisols	8.75 ± 0.11 AB	66.8 ± 1.03 AB	1.2 ± 0.03 BC	70.46 aA
120	Paddy	>50	Rice, wheat/rape	Fluvisols	9.92 ± 0.39 ab	62.83 ± 6 a	1.48 ± 0.04 b	70.17 a
	Upland	>100	Cauliflower, rape, pakchoi, etc.	Fluvisols	10.89 ± 0.72 BCD	75.07 ± 1.23 BCD	1.31 ± 0.04 CD	57.88 aA
300	Paddy	>50	Rice, wheat/rape	Fluvisols	11.67 ± 0.75 ab	72.4 ± 0.46 bcd	1.56 ± 0.05 bc	58.55 a
	Upland	>100	Cauliflower, rape, pakchoi, etc.	Fluvisols	11 ± 0.35 BCD	76.13 ± 0.68 BCD	1.37 ± 0.04 CD	60.86 aA
500	Paddy	>100	Rice, wheat/rape	Fluvisols	14.37 ± 1.01 b	78.43 ± 0.56 d	2.3 ± 0.17 c	65.02 a
	Upland	>100	Cauliflower, rape, pakchoi, etc.	Fluvisols	12.9 ± 1.12 CD	79.97 ± 1.02 CD	1.77 ± 0.04 E	64.44 aA

[a] Values were mean ± SE for clay, silt and TN. Composite samples were used in the analysis of Ti/Zr.
[b] Tillage years were taken as the minimal duration of the present cropping system given by at least 5 local residents.
[c] Based on the FAO/UNESCO Taxonomy.
[d] Values with the same lowercase letters were not significantly different among wetland and paddy soils, and that with the same uppercase letters were not significantly different among wetland and upland soils. Cropping system had no significant effects on TN and Ti/Zr (see Table 2).

fumigation–extraction method after Wu et al. (2006). Total nitrogen (TN) was determined with a C/N analyzer (FlashEA 1112 NC, Thermo, Italy). Total P (TP) was also analyzed with ICP after fusion with lithium metaborate at 1000 °C (Pansu and Gautheyrou, 2006). Available P (P_o) was extracted with 0.5 M $NaHCO_3$ at pH 8.5 and determined by colorimetry. To determine Ti and Zr in the silty fraction, soils were treated with 30% H_2O_2 to fully oxidize organic matters after removing carbonates with diluted HCl, dispersed by shaking with sodium hexametaphosphate for 24 h and then the silty fraction (2–50 μm) was separated by centrifuge. Magnetic susceptibility (MS) was measured with a Bartington Model MS2 susceptibility meter (Bartington, Oxford, England) at the frequency of 0.47 kHz.

2.4. Data analysis

Two-way ANOVA was employed to test the effects of cultivation time and cropping system on soil properties, with cultivation time and cropping system as two fixed factors. Duncan's test was used as the post hoc method. All the statistical analyses were done with SPSS 13.0 (SPSS Inc., USA).

3. Results

3.1. Ratio of Ti to Zr in the silty fraction of soil

The ratio of Ti to Zr (Ti/Zr) in the silty fraction of soil did not show any temporal trend, fluctuating around 64.25 and 65.81 in the paddy and upland soils, respectively (Table 1). Cropping system did not significantly affect Ti/Zr (Table 2). The coefficients of variation of Ti/Zr were low under both cropping systems (10.36% and 7.34% for paddy and upland fields, respectively).

3.2. Readily mobile components

Soil salinity dropped markedly within the first 8 years (from 0.31% to 0.03%) after reclamation but changed slowly thereafter (Fig. 3a). Similarly, NH_4OC-extractable Na^+ and Mg^{2+} showed rapid declines shortly after reclamation and remained at relatively stable levels afterwards (Fig. 3b and c). Unlike other cations, concentrations of Ca^{2+} did not show evident drop until year 500, when its concentration was 3400 μg g^{-1} in the upland fields compared to 4410 μg g^{-1} in the wetlands (Fig. 3d). Cropping system had no significant effect on salinity, Na^+ or Mg^{2+} (Table 2). However, Ca^{2+} concentration was consistently higher in paddy soils than in upland soils throughout all 500 years (Fig. 3d, Table 2).

Soil carbonate content decreased from around 8.79% before year 40 to 2.97% in the 500-year soils, indicating significant decalcification with cultivation time (Fig. 2a). There was no significant effect of cropping system on soil carbonate content (Table 2), but paddy soils had less carbonates than upland soils between year 40 and 120. Soil pH decreased from 8.26 in year 16 to 7.42 in year 500. The temporal trend of pH resembled that of soil carbonates (Fig. 2b) since they were correlated with each other ($r = 0.77$, $P < 0.01$).

3.3. Soil organic carbon and nitrogen

After reclamation of salt marshes, SOC concentration in surface soils (0–8 cm) decreased rapidly from 15.68 g kg^{-1} in wetlands to around 5.70 g kg^{-1} in year 16 (Fig. 4a). Thereafter, SOC increased to 16.36 g kg^{-1} in year 40, but changed slowly to 24.35 g kg^{-1} in year 500. Consequently, the accumulation rate of SOC between year 16 and 40 (0.44 g kg^{-1} year^{-1} on average) was much greater than in the following centuries (0.02 g kg^{-1} year^{-1}). Although a temporary decrease in SOC was observed between year 40 and 75, the overall pattern was clear that SOC increased with cultivation time after an initial decline. SOC in paddy soils was consistently higher than in upland soils (Table 2), but this was less obvious before year 40. In addition, after year 40, SOC accumulation in the upland fields was much less evident than in the paddy fields.

MBC ranged from 48.21 mg kg^{-1} in the 8-year soils to 262.03 mg kg^{-1} in the 500-year soils. MBC followed a similar trend to SOC (Fig. 4b), and they significantly correlated with each other ($r = 0.77$, $P < 0.01$).

The temporal dynamics of LC (data not shown) resembled that of SOC, with the lowest LC in year 16 (1.73 g kg^{-1}) and the highest (4.29 g kg^{-1}) in year 500. Also, paddy soils had significantly higher LC than upland soils (Table 2). There was a general trend that the ratio of LC to SOC (LC/SOC) decreased with soil age (Fig. 4c), peaking in year 16 (30.29%) and reaching the lowest in year 300 and 500 (16.64% and 17.72%, respectively). Paddy soils had significantly lower LC/TOC than upland soils (Table 2). PMC was highest in the marshes (30.88 mg CO_2-C kg^{-1} d^{-1}) and then showed a decreasing trend with time, with the lowest values in year 500 (17.68 and 11.40 mg CO_2-C kg^{-1} d^{-1} in paddy and upland soils, respectively; data not shown). Similarly, the ratio of PMC to SOC (PMC/SOC) also decreased with time (Fig. 4d), from 9.47% in

Table 2
Two-way ANOVA of the effects of soil age (T), cropping system (CS) and the interactive effects of T and CS (T × CS) on soil properties. Both T and LU were treated as fixed factors. Wetland soils were not included in ANOVA.

Soil properties[a]	Source of variation[b]					
	Soil age (T)		Cropping system (CS)		T × CS [c]	
	F	*P*	*F*	*P*	*F*	*P*
Carbonate	48.60	***	1.01	0.32	1.54	0.20
pH	10.42	***	0.06	0.80	2.97	*
Salinity	3.20	*	0.16	0.69	5.05	**
Na^+	6.62	***	0.22	0.64	4.43	**
Ca^{2+}	9.77	***	13.64	**	2.40	*
Mg^{2+}	8.30	***	1.12	0.30	2.80	*
SOC	40.05	***	35.26	***	3.73	**
MBC	14.84	***	16.84	***	8.41	**
LC	16.44	***	12.54	**	3.13	*
LC/SOC	24.30	***	18.48	***	5.03	**
PMC	3.34	0.08	72.30	***	ND	ND
PMC/SOC	34.32	***	1.29	0.30	ND	ND
TN	9.29	***	0.41	0.53	0.68	0.67
PMN	16.62	***	21.25	***	0.74	0.62
PMN/TN	2.33	0.06	25.62	***	0.95	0.48
K^+	1.61	0.18	2.47	0.13	1.65	0.17
TP	11.78	***	18.13	***	1.88	0.12
P_o/TP	8.70	***	18.57	***	0.71	0.64
Fe_d	14.03	***	1.47	0.24	2.38	0.06
Fe_o	7.35	***	40.97	***	2.78	*
Fe_o/Fe_d	17.62	***	29.01	***	3.81	**
MS	16.20	***	35.35	***	3.19	*
Ti/Zr	0.86	0.57	0.21	0.66	ND	ND

[a] Na^+, Ca^{2+}, Mg^{2+}, K^+ were extracted by 1 M NH_4OAc; SOC = soil organic carbon; MBC = microbial biomass carbon; LC = $KMnO_4$-oxidizable carbon; PMC = potentially mineralizable carbon; TN = total nitrogen; PMN = potentially mineralizable nitrogen; TP = total phosphorus (P); P_o = available P; Fe_d (Fe_o) = free (amorphous) Fe oxyhydrates; MS, magnetic susceptibility; Ti/Zr, ratio of Ti to Zr in the silty fraction of soil.
[b] $^*P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.
[c] ND = not determined. The interactive effect of T × CS for PMC, PMC/SOC and MS could not be tested because only one composite sample was analyzed for each combination of T and CS.

the marshes to 1.90% in the 500-year croplands. In fact, PMC/SOC was significantly correlated with LC/SOC ($r = 0.57$, $P < 0.01$). It was notable that PMC/SOC decreased rapidly in the first 40–120 years but only changed slowly thereafter. No significant effect of cropping system on PMC/SOC was detected (Table 2).

Like SOC, TN dropped from 1.11 g kg^{-1} in marsh soils to 0.63 g kg^{-1} in year 16 and then increased to 2.03 g kg^{-1} in year 500 (Table 1). The effect of cropping system on TN was insignificant (Table 2), but it could be seen that paddy soils had higher TN than upland ones between year 120 and 500 (Table 1). The labile nitrogen, represented by PMN (Fig. 5a), changed in a similar manner to SOC with time, but PMN was significantly higher in upland than in paddy fields (Table 2). PMN/TN before year 16 was largely lower than in older soils (data not shown). Also, paddy soils had significantly lower PMN/TN values than upland soils (Table 2).

3.4. Potassium and phosphorous nutrition

The NH_4OAc-extractable K^+ did not show a clear temporal trend after an initial rapid drop immediately after reclamation (Fig. 5b). Overall, cropping system did not significantly influence K^+ (Table 2), but it could be seen from Fig. 5b that upland soils had higher concentrations of K^+ than paddy soils at ages between year 40 and 300.

TP increased evidently during the first 75 years of cultivation (Fig. 5c). However, TP in paddy soils did not significantly change thereafter, fluctuating around 1319 mg kg^{-1}, and TP in upland soils even dropped in year 300. Soils younger than 40 years had clearly higher ratio of available P to TP (P_o/TP) than older soils (Fig. 5d). Both TP and P_o/TP of upland soils were significantly higher than that of paddy soils (Table 2).

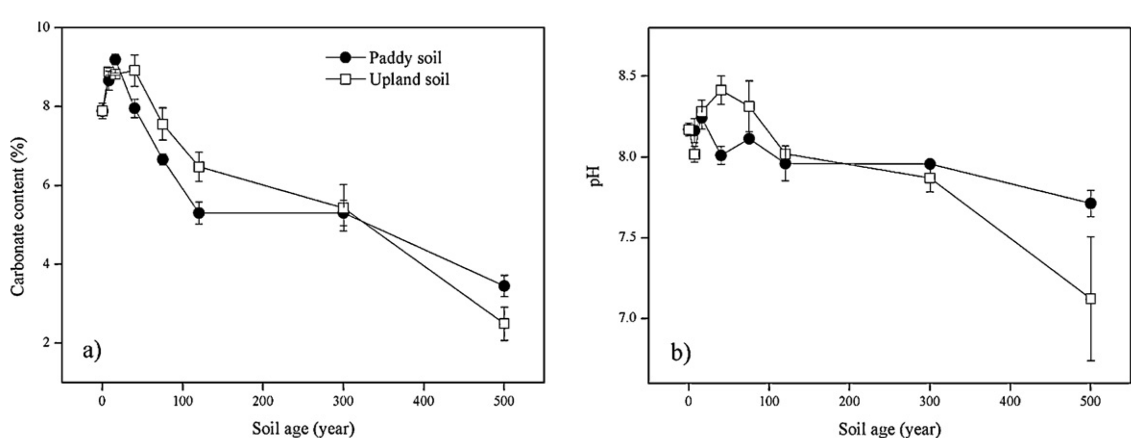

Fig. 2. Changes in (a) soil carbonate content and (b) pH with time. Error bars represented one SE.

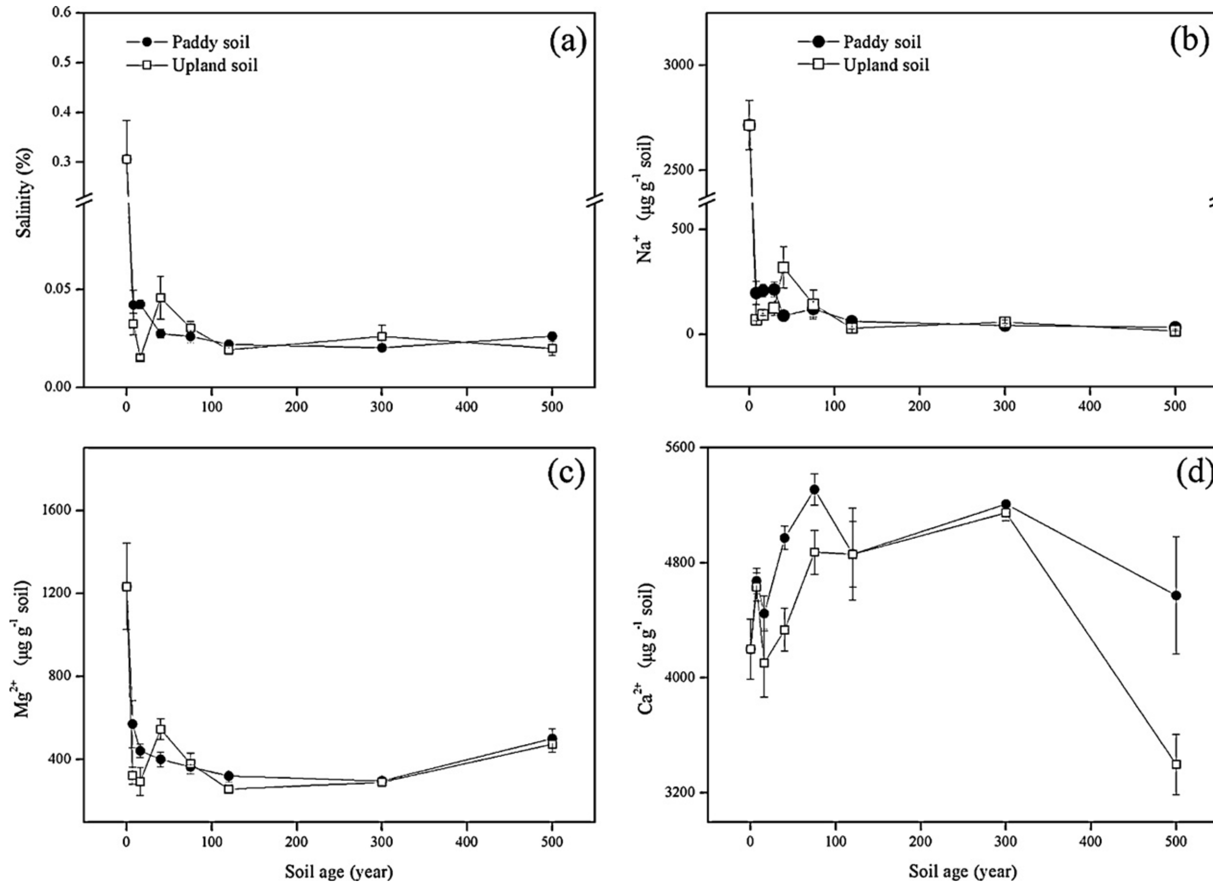

Fig. 3. Changes in (a) salinity and NH_4OAc-extractable (b) Na^+, (c) Mg^{2+} and (d) Ca^{2+} along the chronosequence. Error bars identified one SE.

3.5. Solid features: iron fractions and magnetic susceptibility

Fe_o showed a decreasing trend throughout all 500 years (Fig. 6a). Fe_d was significantly correlated with SOC ($r = 0.65$, $P < 0.01$) and dropped in the first 16 years (data not shown), concurrent with decreases in Fe_o. Thereafter, Fe_d increased to some extent but did not show a clear trend after year 40, resulting in decreases in the ratio of Fe_o to Fe_d (Fe_o/Fe_d, Fig. 6b) with time. Changes in Fe_o and Fe_o/Fe_d were more dramatic in the first 120 years than in the subsequent centuries. In the 8-year soil profiles, Fe_o increased with depth and this trend was more evident in paddy than in upland fields (Fig. 6c), indicating leaching of Fe_o induced by wetland reclamation. Cropping system did not significantly influence Fe_d, but Fe_o and Fe_o/Fe_d were both significantly higher in paddy than in upland soils (Table 2).

Soil MS was highest in the wetlands, and showed a clear decreasing trend in paddy soils. However, this mainly occurred before year 120 and relatively slow decreases were observed after that. MS in upland fields slightly decreased after reclamation of salt marshes, but did not change evidently between year 40 and 500 (Fig. 7). Cropping system had a significant influence on MS, with paddy fields having lower MS than upland fields (Table 2).

4. Discussion

4.1. Chronosequential changes in topsoil chemical properties

4.1.1. Uniformity of soil parent materials

Uniformity of soil parent materials, i.e. soils have the same origin, is important for the use of soil chronosequences (Schaetzl, 1998). Schaetzl (1998) strongly recommended using inert elemental composition of particle-size soil fractions which are larger than clay to detect the ununiformity of soil parent materials, because clay was mobile and easy to weather. Two inert elements, Ti and Zr, in clay-free soil fractions have often been measured for this aim (Schaetzl, 1998; Tsai and Chen, 2000). In this study, Ti/Zr ratio in the silty fraction (2–50 μm) was used to infer parent material uniformity, which was also adopted by Chen and Zhang (2009) for coastal soils elsewhere. We found insignificant differences in Ti/Zr among all soils and fairly low (<11%) coefficients of variation (CV) for both paddy and upland soils along the chronosequence. Some studies used much higher CV (e.g. 100% in Chapman and Horn (1968)) to judge parent material ununiformity. Considering the strong anthropogenic disturbances in agricultural soils, it could be concluded that parent materials of our soils largely originated from the same source.

However, it was still unavoidable that heterogeneity existed in soil texture (Table 1). The 16-year upland soils were more coarse-textured compared to other soils, which might be because these soils were located by the roadside and subject to artificial transport or aeolian erosions. Nevertheless, this would not affect the overall temporal patterns of soil properties.

4.1.2. Temporal trends of main soil chemical properties

Our results indicated strong leaching processes in soil after reclamation of coastal wetlands. Desalinization of soil was rapid once supply of seawater was cut off (Fig. 3a–c), as in the nearby Hangzhou Bay (Iost et al., 2007). Strong leaching also caused evident decalcification (Fig. 2a). However, Ca^{2+} did not show evident reduction with time, probably due to the replenishment of Ca^{2+} by the abundant soil carbonates (>5.3% before year 300). Soil pH significantly decreased along with decalcification. Two 500-year upland soils even had pH values of 6.77 and 6.71, suggesting possible soil acidification in the future. In the Hangzhou Bay, Chen

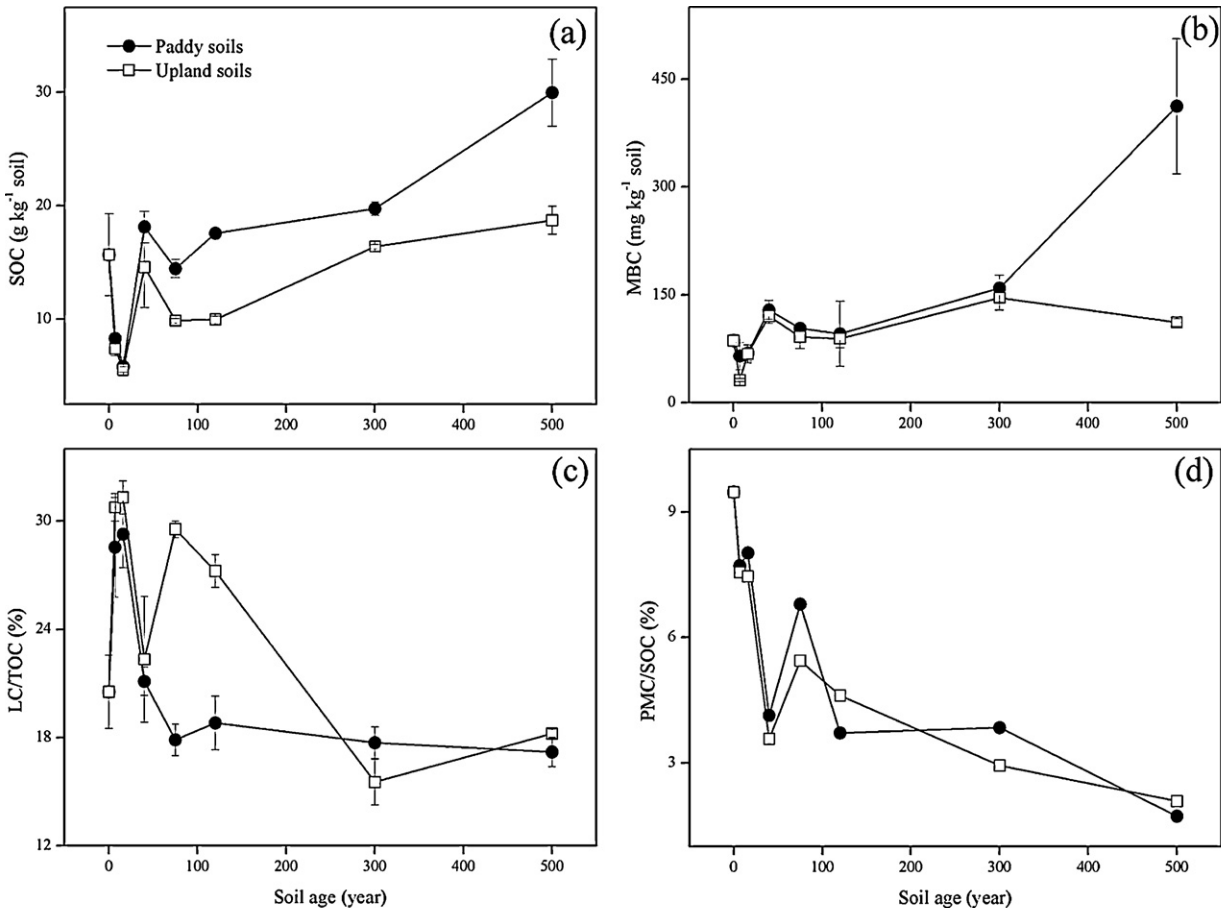

Fig. 4. Temporal trends of (a) soil organic carbon (SOC), (b) microbial biomass carbon (MBC), (c) ratio of KMnO4-oxidizable C (LC) to SOC (LC/SOC) and (d) ratio of potentially mineralizable C (PMC) to SOC (PMC/SOC). Error bars indicated one SE. SE was not given in (d) because replicate soils were composited for incubation.

and Zhang (2009) reported soil pH of 6.3 after 700 years of cultivation on reclaimed coastal wetlands. Luo (2008) even found pH of 4.22 in soils reclaimed 2000 years ago, which was considered to be caused by leaching of soil bases as well as overuse of chemical fertilizers. Considering the strong leaching of soil carbonates and high fertilization rate (400 kg ha^{-1} year^{-1}; Li, 2006), future soil acidification is possible for the Chongming Island, as has widely occurred in China's croplands (Guo et al., 2010).

It was notable that SOC initially declined after reclamation but then recovered to levels close to that of wetlands within 40 years (Fig. 4a). A similar temporal pattern of SOC was also observed by Iost et al. (2007) for reclaimed soils in the Hangzhou Bay. Obviously, the initial SOC loss was induced by drainage of soils, which was commonly seen after wetland reclamation (Li and Pan, 2009; Zedler and Kercher, 2005; Zhang et al., 2008). The subsequent SOC accumulation might be due to the high agricultural C inputs and protection of SOC by soil minerals. Most wetland SOC was not stabilized by soil minerals and hence subject to rapid decomposition once exposed to air (Davidson and Janssens, 2006), which was also reflected by the high PMC/SOC ratio of our wetland soils (Fig. 4d). However, SOC in croplands could be physically stabilized by soil aggregates or chemically stabilized by organo-mineral associations (Six et al., 2002). This might be the reason why SOC stability increased (i.e. LC/SOC and PMC/SOC decreased) with cultivation time (Fig. 4c and d). Zhou et al. (2009b) suggested binding of organic matter to Fe/Al oxyhydrates as an important mechanism of SOC stabilization in China' paddy soils. This might have also played a role in SOC accumulation here given the significant correlation between SOC and free Fe oxyhydrates ($r = 0.65$, $P < 0.01$).

The buildup of N and P indicated that soil fertility improved after 500 years of cultivation (Fig. 5a and c). Soil organic matter was likely the main source of soil N supply because both TN ($r = 0.79$, $P < 0.01$) and PMN ($r = 0.47$, $P < 0.01$) were significantly correlated with SOC. The buildup of TP should be a result of P fertilization. There was a long history of using P-rich organic fertilizers on the Chongming Island (e.g. manure and compost), and chemical P fertilizers were commonly used after the 1950s (Zhou and Ji, 1989). Huang et al. (2008) reported a 29.05% increase of soil available P on the island in 2004 compared to that in the early 1980s. With little external P inputs in natural soils, P contents usually decrease against time due to losses of dissolved P (Hedin et al., 2003). In contrast, P fertilization has caused widespread soil P increases in the Yangtze River delta region (Darilek et al., 2010). However, increases of P slowed down after year 75 in our study, suggesting that cropland P contents would not increase infinitely even with steady inputs of P. This agreed with the observation of Zhang and He (2004) that soil P accumulation was most obvious in the first 30 years of rice cultivation.

Crystallinity of Fe oxyhydrates (represented by Fe_o/Fe_d) clearly increased with cultivation time (Fig. 6). Decreases in Fe_o and Fe_o/Fe_d were often seen as soil became mature (e.g. Bockheim et al., 1996) and also observed in our study. However, the immediate drop of Fe_o after reclamation should be mainly due to leaching of amorphous Fe oxyhydrates as evidenced by the increasing Fe_o with depth, especially in the 8-year paddy fields. Fe could form dissolvable complexes with organic ligands under the reduced environments of natural or artificial wetlands and was subject to leaching (Luther et al., 1992). Dong and Xu (1991) reported strong leaching of Fe oxyhydrates at the early stage of rice cultivation on

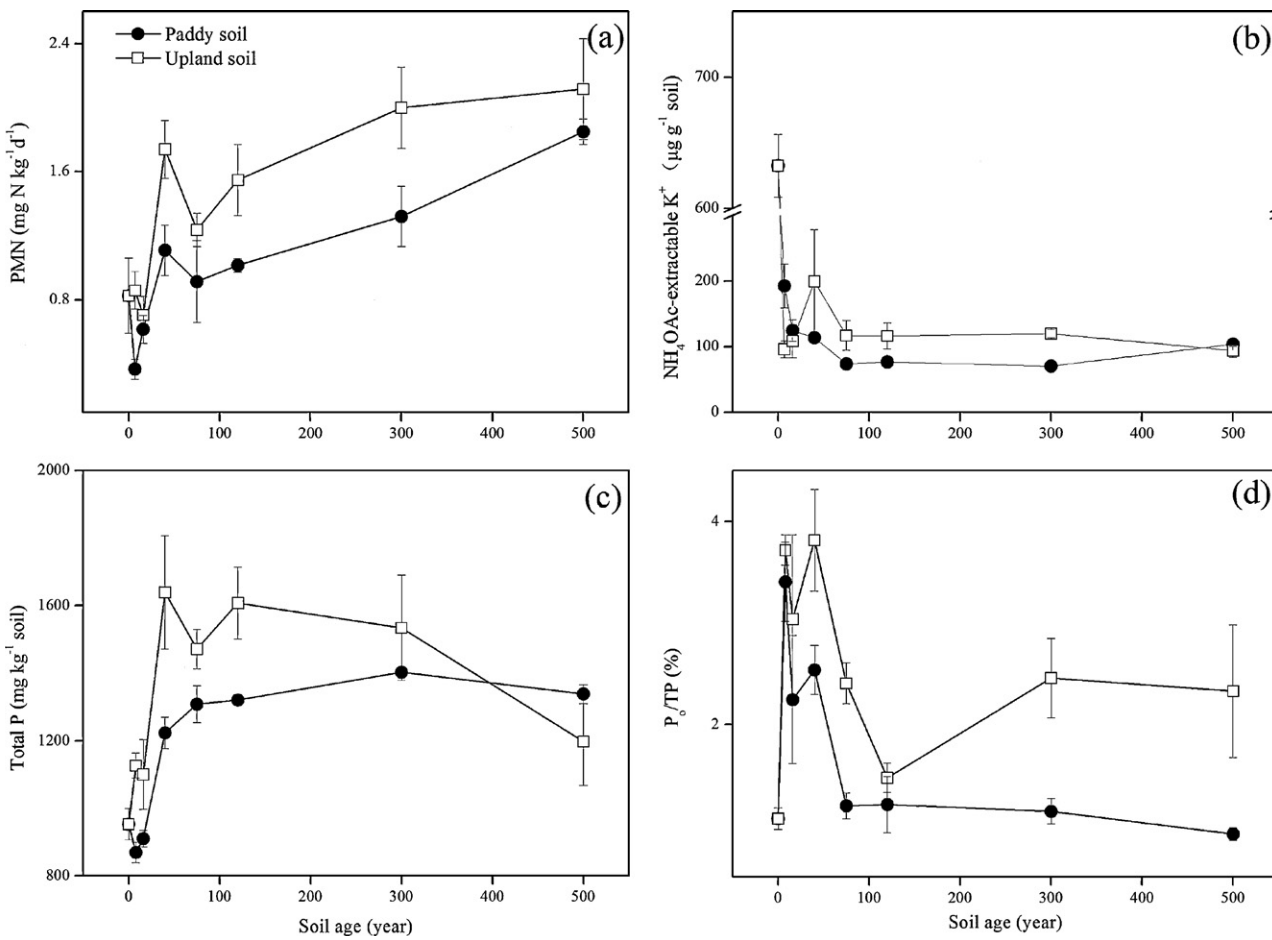

Fig. 5. Changes in (a) potentially mineralizable N (PMN), (b) NH_4OAc-extractable K^+, (c) total P (TP) and (d) ratio of available P (P_o) to TP (P_o/TP) with time. Error bars identify one SE.

previous swamps. Changes in Fe oxyhydrates would profoundly influence soil structure and soil functioning, such as carbon and sulfur cycling (Kögel-Knabner et al., 2010).

Overall, soil chemical properties showed directional trends during 500 years of cultivation after reclamation. Although the present cropping systems might have once been interrupted, our results would still provide useful information if duration of paddy or upland cropping increased along the chronosequence. This was confirmed by measurements of MS. Generally, MS enhanced with soil age due to the formation of magnetic materials (Fine et al., 1992). However, under anaerobic conditions, high-MS magnetic materials would be reduced to low-MS ones (Lu, 2000), and longer duration of rice cultivation usually resulted in lower soil MS, a phenomenon absent in upland fields (Lu, 2003). Also, paddy soils usually had lower MS than upland soils (Lu, 2000). In this study, we observed a clear decreasing trend of MS against time under paddy rice cropping (Fig. 7), proving that rice cultivation duration increased along the chronosequence. Chen and Zhang (2009) also reported decreasing MS along a 1000-year chronosequence of paddy soils. Compared to paddy soils, upland soils showed MS that was obviously higher and did not change significantly after 40 years, indicating no significant loss of magnetic materials. The initial drop of MS should be due to leaching of Fe oxyhydrates (Fig. 6c), which contained most soil magnetic minerals (Fine et al., 1992). It could thus be concluded that upland soils had not been flooded for long time, i.e. upland cropping persisted during most time of the past 500 years. Overall, the duration of paddy rice or upland cropping indeed increased along the chronosequence. The evidence might be only qualitative and indirect, but there was no better way to compare cultivation duration among soils to our knowledge.

One may suspect that the temporal patterns of soil properties solely resulted from evolution of land management over time, which was unlikely. Main soil properties, such as salinity, SOC, PMN, TP, Fe_o and Fe_o/Fe_d, changed most significantly in the first 40 years, when reclaimed soils had all been under modern management uniformly instructed by the Chongming Agriculture Committee (Zhou and Ji, 1989). Prior to this, it was unclear how agricultural customs had varied over time on the island, but soils changed slowly after 40 years of cultivation. Hence, pedogenetic processes rather than management factors should be mainly responsible for the observed soil chemical changes over time. However, short-term decreases in such properties as SOC (Fig. 4a), TN (Table 1) and PMN (Fig. 5a) between 40 and 75 years might be related to land management. There was likely overuse of N fertilizers in the 40-year soils, because their TN was close to that of 500-year soils (Table 1), which might partly explain the high SOC in year 40. However, this temporary management effect did not change the overall patterns of soil properties at a time scale of 500 years. Provided enough caution taken in data interpretation, results derived from chronosequence studies would still give useful insights into long-term dynamics of agricultural soils.

4.2. Land use effects on topsoil chemical properties

Even at the time scale of centuries, paddy rice cropping showed a greater potential of SOC sequestration than upland cropping in the topsoil, which was consistent with Luo (2008) and Cheng et al. (2009). However, this became evident only after 40 years of cultivation (Fig. 4a). Cheng et al. (2009) observed a similar pattern along a 1000-year cultivation chronosequence, and they suggested that about 50 years are needed to differentiate paddy from upland soils in terms of SOC in surface horizons. In addition, we found that SOC in paddy fields continued to increase even after centuries of cultivation, while the increase was not evident in upland fields after 40 years. All these were in accordance with previous studies stating that paddy soils in China had larger SOC sequestration potential than upland soils (e.g. Cai, 1996; Pan et al., 2003). However, SOC accumulation rate in paddy soils became as low as 0.02 g kg^{-1} $year^{-1}$ after 40 years of cultivation, which was hardly detectable at time scale of decades. This agreed with the finding of Li et al. (2005) that SOC increased evidently only in the first 30 years of rice cultivation on C-depleted soils but insignificantly in the next 50 years. Presumably, SOC in paddy fields could easily reach a near-equilibrium state in the first several decades of cultivation and then approach slowly to an equilibrium level. According to Zou et al. (2011), 700 years might be needed for this equilibrium to be seen.

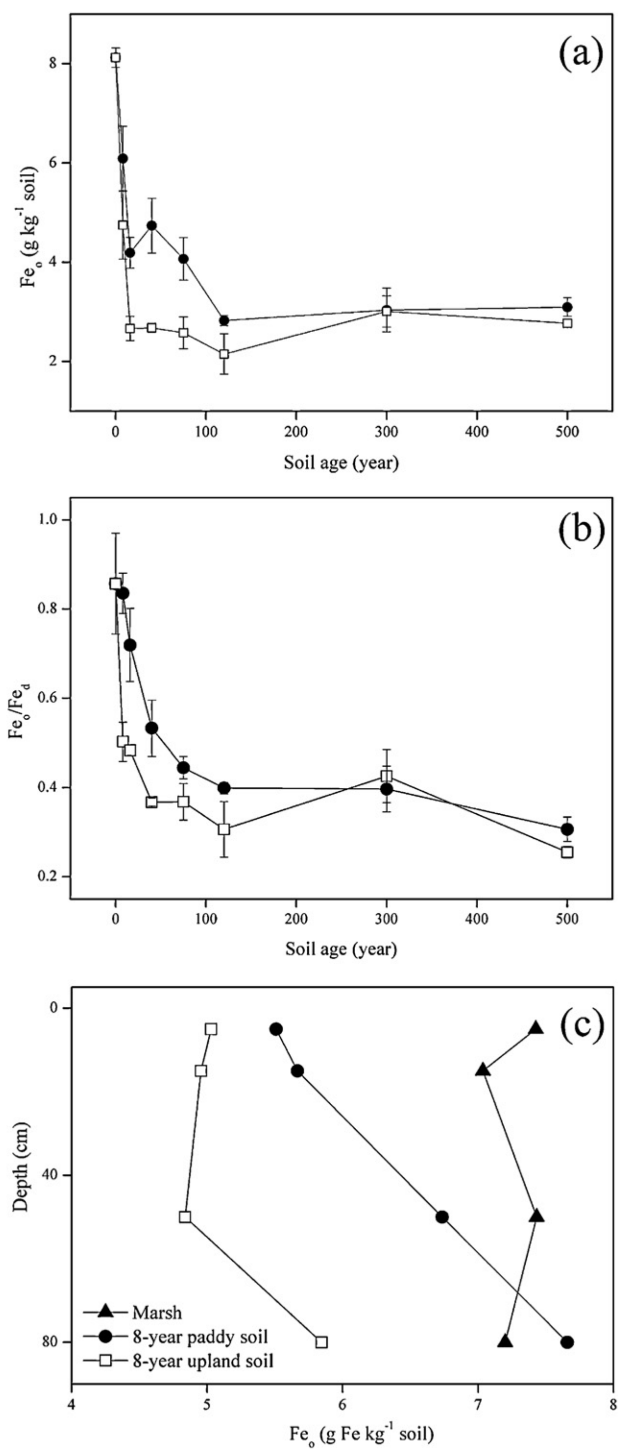

Fig. 6. Chronosequential changes in (a) amorphous Fe oxyhydrates (Fe_o) and (b) the ratio of Fe_o to Fe_d (Fe_o/Fe_d). Also shown were (c) depth profiles of Fe_o in salt marshes and the 8-year soils. Error bars identify one SE.

Several mechanisms might be responsible for the higher SOC in paddy soils relative to upland soils. Firstly, this could result from differences in return of plant stubbles to soil. Annually, about 2.35 t ha^{-1} stubble was returned to paddy soils on the Chongming Island, while there was almost no intentional return of plant residues to uplands soils. There has been a positive correlation between carbon inputs via stubbles and SOC accumulation of paddy fields in southern China them (Zhou et al., 2009a). Secondly, there might be stronger mineral protection of SOC in paddy fields. Higher contents of Fe_o, which had a large specific surface area for adsorption of organic matter, were found in paddy than in upland soils (Fig. 6a). There were usually positive relationships between Fe_o and SOC accumulation under paddy rice cropping (Pan et al., 2003). Based on carbon fractionation data from long-term stations in China, Zhou et al. (2009b) suggested that Fe oxyhydrates in micro-aggregates might be important for the high SOC accumulation of paddy soils. In addition, the higher Ca^{2+} of paddy soils (Fig. 3d) could to some extent contribute to the binding of organic matter to mineral surfaces (Nguyen et al., 2004). Finally, decomposition of SOC was retarded by flooding during the rice growth period in paddy fields, but not in upland fields (Kögel-Knabner et al., 2010). Other mechanisms underlying the stronger SOC accumulation of paddy soils could be associated with fungi-to-bacteria ratio (Liu et al., 2011) as well as formation of phytoliths (Gong et al., 2007), an organo-mineral complex that preserved organic carbon but was absent under upland cropping.

The higher Fe_o and Fe_o/Fe_d of paddy soils than that of upland soils agreed with previous studies (Cheng et al., 2009; Chi et al., 2009). Paddy soils were usually characterized with high concentrations of dissolved organic matter during the flooding season (Kögel-Knabner et al., 2010), favoring the translocation of Fe in clay minerals and the formation of amorphous Fe oxyhydrates (Kögel-Knabner et al., 2010).

Higher concentrations of Ca^{2+} in paddy soils than in upland soils (Fig. 3d) were possibly associated with Ca^{2+} concentrations in irrigation water. River water of the Chongming Island had Ca^{2+}

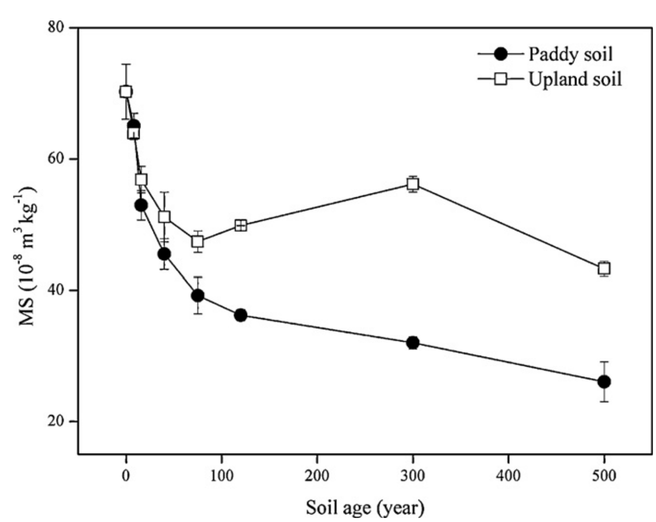

Fig. 7. Magnetic susceptibility (MS) of paddy and upland soils along the chronosequence. Error bars represented one SE.

concentrations as high as 134–220 mg L^{-1} in the rainy season (Le et al., 2009), which was obviously influenced by the invasion of seawater in the Yangtze Estuary. Also, paddy fields during the dry farming period had higher soil respiration rates than upland fields (Iqbal et al., 2008), which would cause larger partial CO_2 pressure in soil atmosphere and accelerate dissolution of carbonates.

Despite the higher SOC, paddy soils revealed lower levels of nutrients (N, P, K) than upland soils. The lower N availability (indicated by PMN and PMN/TN, Fig. 5) in paddy soils was also noticed by Luo (2008) in Hangzhou Bay. The mechanisms remain unclear. Reduced N bioavailability in paddy soils over time was found by Olk et al. (1996), and Schmidt-Rohr et al. (2004) suggested this to be a result of tight binding of N to lignin. Paddy soils also had lower TP and P_o/TP than upland soils, which probably resulted from reduction of Fe–P compounds and subsequent leaching. Paddy fields usually need less P fertilizer than upland fields because a significant amount of fixed P could be released by reduction of Fe–P during rice cultivation (Li, 1992). It was also notable that paddy soils had lower K availability than upland soils between year 40 and 300 (Fig. 5b), possibly due to strong leaching and plant acquisition of K in paddy fields (Gong, 1983). On the Chongming Island, K fertilization rate in paddy soils has increased by 5.4 times since the late 1980s (Yang, 2006). Li (2006) estimated that 10% of applied K was leached from croplands. This would exacerbate K pollution in the Yangtze Estuary water.

4.3. Implications for managing soils reclaimed from coastal wetlands

Overall, five centuries of cultivation on previous coastal wetlands had created relatively fertile soils, as shown by the low salinity, nearly neutral pH, high SOC and MBC levels and improved nutrient status in the oldest soils. However, we found a transition phase (40 years in this study) of soil following wetland reclamation, when soil properties changed more markedly than in the subsequent centuries. Notably, soil fertility appeared low and declined with time during the first 16 years of the transition phase, as reflected by the decreasing SOC levels and N availability. Microbial biomass was also small during this period (Fig. 4b), and soil P accumulation (Fig. 5c) had just started. The declining soil fertility might be a common problem for newly reclaimed wetlands worldwide, because rapid loss of soil organic matter generally accompanied reclamation (Zedler and Kercher, 2005), and cultivation time was still too short to improve soil fertility. Given the key role of organic matter in soil fertility, management of new aerated wetland soils should aim to improve soil organic matter contents. Relatively heavy application of chemical fertilizers containing N, P and K might be also necessary for such soils, as proposed by Iost et al. (2007).

The greater SOC accumulation of paddy soils than upland soils suggested that paddy rice cropping might be more efficient in improving the fertility of young soils reclaimed from coastal wetlands. Hu et al. (2008) found no indication of soil degradation even after 2000 years of rice cultivation on such soils. In fact, the rice-based cultivation has often been recognized as an environment-friendly and sustainable agricultural land use (Hu et al., 2008; Yoon, 2009; Zou et al., 2011).

5. Conclusions

During five centuries of cultivation after reclamation of coastal wetlands, soils showed a clear pattern of evolution even in the frequently disturbed plow layer. The major soil chemical changes included rapid desalinization and decalcification, accumulation of soil organic matter, buildup of soil N and P, and increases in the crystallinity of Fe oxyhydrates, which mostly proceeded at much higher during the first several decades after reclamation than in the following centuries. Cropping system strongly influenced soil dynamics. Notably, throughout all five centuries, paddy rice cropping was consistently superior to upland cropping in improving soil organic matter levels. Centuries of cultivation seemed to have increased overall soil fertility, but there existed a transition phase of the soil system shortly after reclamation of coastal wetlands, when the relatively low soil fertility should be considered by land managers.

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