

Chemical soil properties of reclaimed marsh soil from Zhejiang Province P.R. China

Susanne Iost^{a,*}, Dirk Landgraf^b, Franz Makeschin^a

^a *Institute of Soil Science, Faculty of Forest, Geo and Hydro Sciences, Dresden University of Technology, P.O. 1117, D-01735 Tharandt, Germany*

^b *Research Institute of Post-Mining Landscapes Inc., Brauhausweg 02 D-03238 Finsterwalde, Germany*

Received 24 February 2006; received in revised form 2 April 2007; accepted 5 August 2007

Available online 27 September 2007

Abstract

Initial pedogenesis of reclaimed saline marsh soils was studied along a chronosequence of reclaimed land at Hangzhou Bay, Zhejiang Province, P.R. China. The objective was to compare soil development of these soils with processes known for natural saline marsh soil development and to evaluate the presented form of artificial land recovery against the background of increasing population densities in China. Electrical conductivity (water) and exchangeable sodium percentage decreased rapidly after reclamation started. The decrease in pH and carbonate content suggest an incipient decalcification. Soil organic carbon decreased in the first 30 cm within 20 years, caused by mineralization of the organic sea sediments. After this process an accumulation of soil organic carbon due to organic matter input as a result of farming was observed. At all sites total contents of calcium, magnesium and potassium were classified as elevated to high and decreased slightly within 31 years after reclamation and commencement of agricultural use. Only total phosphorus increased after construction of embankments, attributed to the application of fertilizer phosphorus. Available nutrient contents developed differently but none showed significant trends. Calcium slightly decreased as an effect of reclamation. Processes of pedogenesis were comparable to those known for natural marshes, but had an initial character. The reclamation of land in the presented manner is considered important to support high and growing population densities in China. However, agricultural management and fertilizer application has to be carefully evaluated.

© 2007 Elsevier B.V. All rights reserved.

Keywords: Marsh soil genesis; Yangtze

1. Introduction

Soil erosion in the Loess plateau and other regions of P.R. China contributes to high sediment loads on Chinese rivers. The Yangtze River carries $0.5 \cdot 10^9$ t of sediment per annum (Liu et al., 2003) to the East China Sea. Between 25 and 50% of the suspended material is deposited close to the river mouth (Chen et al., 2001; Liu et al., 2002) and further 25% is transported southwards where the sediments also remain in coastal zones, like Hangzhou Bay (Liu et al., 2002). Smaller rivers like the Qiantang River also contribute to high sediment loads and the development of extensive natural tidal flats along the coast of

Hangzhou Bay. During the past decades not only have natural tidal flats been reclaimed for agriculture, housing and industry to alleviate the pressure of the increasing population (Shi et al., 2002). Furthermore dams are constructed that facilitate the sedimentation of suspended material in areas where natural sedimentation would not occur due to tidal movement. Marsh geogenesis (Giani and Landt, 2000) in the studied region of Shangyu County has been realized artificially by dam construction, pumping of suspended material into the enclosed area and drainage by artificial canals. In general natural marsh soil pedogenesis is characterized by development of soil structure due to dewatering and compaction, oxidation of reduced iron-, manganese- and sulphur compounds including the formation of accumulating horizons, decalcification, desalinisation, recharge of soil colloids and decomposition of organic matter (Schroeder and Bruemmer, 1969; Bruemmer et al., 1971; Mueller-Ahlten, 1994a,b; Giani and Landt, 2000; Giani et al.,

* Corresponding author. Institute of Soil Science, Dresden University of Technology, Piennner Str. 19, 01737 Tharandt. Tel.: +49 35203 3831244; fax: +49 35203 3831388.

E-mail address: meusel.susanne@gmx.de (S. Iost).

2003). In diked and drained marshes these processes are accelerated, especially sulphide oxidation which causes change of redox conditions, decline of pH and altered mobility of phosphorus, iron and other metals (Portnoy, 1999). Furthermore, decomposition of sedimentary organic matter after lowering of the water table and aeration is a well established process in diked marshes. The objectives of this study were (i) to describe processes in marsh soils that developed as a consequence of artificial marsh geogenesis and (ii) to evaluate rate and intensity of pedogenesis as well as (iii) suitability of the reclaimed land for intensive agricultural use. This was realized by determining different chemical and physical soil parameters along a chronosequence of five sites reclaimed in different years.

2. Material and methods

The research area is located in the county of Shangyu, Zhejiang Province, P.R. China, between latitudes 30°07'03" N and 30°10'33" N and longitudes 120°42'10" E and 120°47'04" E. This area covers about 17000 ha. The climate is classified as subtropical monsoon with average annual temperatures between 15 and 19 °C and annual precipitation of 1300 mm. During July and August evapotranspiration is very high and the water balance in the soils negative (Shi et al., 2002). The soils studied were reclaimed in 1969, 1976, 1984, 1991 and 1996, respectively. Except for 1996 all sites were intensively agriculturally managed. The 1996 site was left to succession fallow. Table 1 summarizes soil properties that resulted from preliminary investigations of this study. Each site was divided into six subsites, each of the subsites was sampled in autumn 2000 using a soil auger to a depth of

100 cm. At each subsite 20 soil cores were taken and pooled according to four depth units; 0–10 cm, 10–30 cm, 30–60 cm and 60–90 cm. The lowest 10 cm were rejected. This procedure resulted in six composite samples for each site and depth. Samples were dried at 40 °C and sieved (2 mm plastic sieve).

Total calcium (Ca_t), magnesium (Mg_t), potassium (K_t) and phosphorous (P_t) content for each composite sample were determined after digestion with Aqua Regia, according to ISO 11466 (1995). Concentrations of the respective nutrients were determined by inductively coupled plasma optical emission spectrometry (type: Liberty 220 ICP-OES by Varian; Palo Alto, USA).

Available contents of calcium (Ca_{AA}), magnesium (Mg_{AA}) and potassium (K_{AA}) were estimated by extraction with 1 M ammonium acetate according to Warncke and Brown (1998) at pH 7 (soil solution ratio 1:10, shaking time 5 min). Concentrations were determined by atomic absorption spectroscopy (AAS) (type: GBC 933 AA; by GBC; Dandenong, Australia). As availability index for phosphorous, Olsen P (P_O) was used (Frank et al., 1998). To this purpose, extraction with 0.5 M $NaHCO_3$ at pH 8.5 (soil-solution ratio 1:10, shaking time 30 min) was performed, P concentration in the extract being determined photometrically (type: GBC 911 by GBC, Dandenong, Australia) at 882 nm (Frank et al., 1998).

The NH_4Cl extractable cations were determined according to Schlichting et al. (1995). K concentrations were measured with an AAS (GBC, Model GBC 933, Dandenong, Australia), the other cations with ICP-OES (Plasma II, Perkin Elmer, Waltham, USA). Exchangeable sodium percentage (ESP) was calculated as follows: $[NH_4Cl\text{-extractable } Na^+ (\mu eq\ g^{-1}\ soil)] * \sum [NH_4Cl\text{-extractable cations } (\mu eq\ g^{-1}\ soil)] * 100\%$ (Richards, 1954). Electrical conductivity (EC_E) was determined according to Schlichting et al. (1995) in deionized water using a multiparameter analyzer (18.28 Eijkelkamp; Giesbeek, Netherlands).

Statistical analysis was carried out using Statistica 6.0 (Statsoft® Europe, Hamburg, Germany) and SPSS 10 (SPSS München, Germany) software. Obtained data was tested for correlation between content of the respective nutrient and elapsed time after reclamation using Spearman's correlation coefficient (r_s) based on the assumption that the data was not normally distributed. Average contents of selected available nutrients are represented by the median. Data was tested on differences between horizons and sites using the Mann–Whitney- U -test. Differences were significant if probability of error (p) was smaller than 0.05.

3. Results

Along the chronosequence few significant changes were observed. The pH ranged between 8 and 9 and declined only in 0–10 cm significantly ($r_s=0.97$). The EC_E ranged from 2.5 to 8.0 $mS\ m^{-1}$ and was highest at the site which was reclaimed in 1996 in all studied depths. Carbonate content in the soil varied between 4.9 and 6.4% in the respective horizons. This amounted to a proportion of 43.2 to 76.7% of total carbon. Carbonate content was lower in the upper horizons. Soil organic carbon content in 0–10 and 10–30 cm declined during the first five

Table 1
Soil chemical and physical properties of the study sites in Shangyu county, P.R. China

Soil depth	Site	Clay	Silt	Sand	pH _(H₂O)	EC _E	CaCO ₃	SOC	TN
0–10 cm	1969	6.51	92.64	0.85	8.0	3122.8	4.9	7.6	1.05
	1976	5.42	94.00	0.58	8.1	2671.0	5.4	6.7	0.90
	1984	6.02	88.86	5.12	8.1	2550.6	5.6	6.0	0.79
	1991	5.06	84.87	10.09	8.2	2604.8	5.1	5.3	0.65
	1996	7.57	91.76	0.67	8.6	5071.8	6.2	8.1	0.55
10–30 cm	1969	7.69	91.57	0.73	8.4	4162.1	5.9	4.0	0.39
	1976	5.58	93.93	0.49	8.3	3546.8	5.9	3.4	0.29
	1984	6.16	89.18	4.66	8.5	3865.6	6.0	3.7	0.33
	1991	5.08	82.91	12.01	8.5	3077.3	5.5	3.3	0.29
	1996	7.76	91.90	0.34	8.7	7528.3	6.6	6.1	0.51
30–60 cm	1969	8.26	91.36	0.38	8.6	4435.0	6.3	2.6	0.35
	1976	4.97	94.32	0.71	8.6	3632.9	6.0	2.5	0.25
	1984	5.35	91.92	2.72	8.7	3958.0	6.0	2.8	0.28
	1991	5.85	86.92	7.23	8.5	2984.7	5.9	3.1	0.46
	1996	7.42	92.13	0.45	8.6	8010.4	6.3	4.4	0.41
60–90 cm	1969	5.92	93.49	0.59	8.9	4796.6	6.2	2.4	0.25
	1976	6.46	93.00	0.55	8.7	3717.7	6.2	2.8	0.31
	1984	5.76	92.21	2.03	8.9	4008.6	6.1	2.6	0.31
	1991	8.34	89.23	2.43	8.5	3106.3	6.1	4.5	0.58
	1996	8.07	91.52	0.41	8.6	7738.5	6.4	5.5	0.47

EC_E: electrical conductivity; CaCO₃: carbonate content of the dry soil; TC: total carbon; SOC: soil organic carbon; TN: total nitrogen.

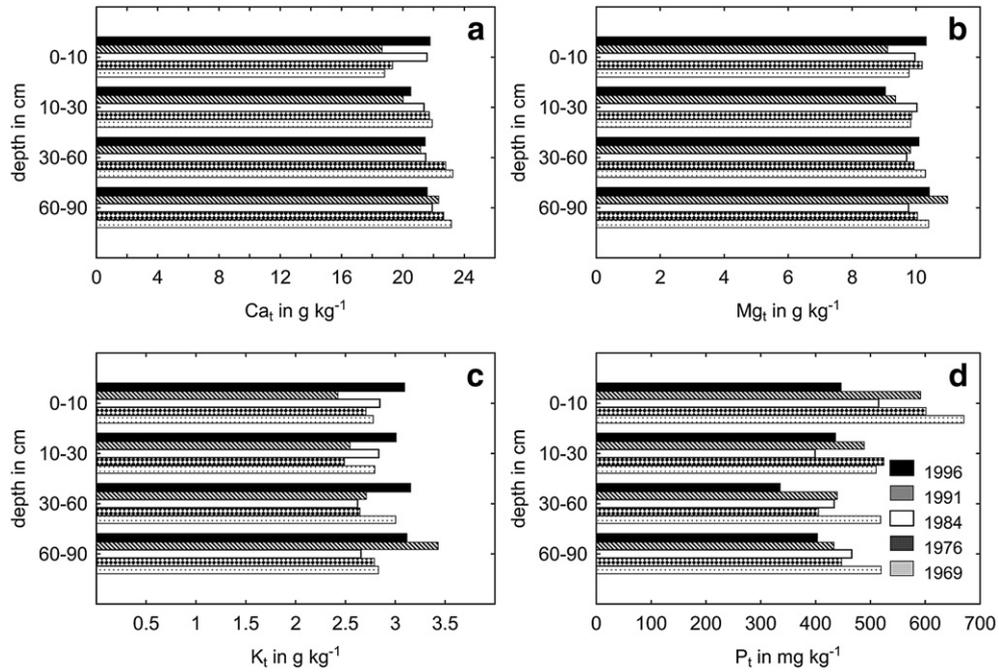


Fig. 1. Total contents of Ca (a), Mg (b), K (c) and P (d) in all study sites and four depths reclaimed in 1969, 1976, 1984, 1991 and 1996.

years after embankment from 8.1 to 5.3 and 6.1 to 3.3 g kg⁻¹, respectively. This was due to mineralization of organic matter in the diked sediments. Intensive agricultural use (i.e. incorporation of plant residues in to the soil) caused the SOC to increase to 7.6 g kg⁻¹ in 0–10 cm and to 4.0 g kg⁻¹ in 10–30 cm at the sites

reclaimed in 1969. In 30–60 and 60–90 cm SOC significantly decreased with time after embankment ($r_s=0.9$ in both). This was also due to mineralization of organic matter in the sediments. Total nitrogen content varied between 0.25 and 1.05 g kg⁻¹ and tended to be higher in 0–10 cm and 10–30 cm

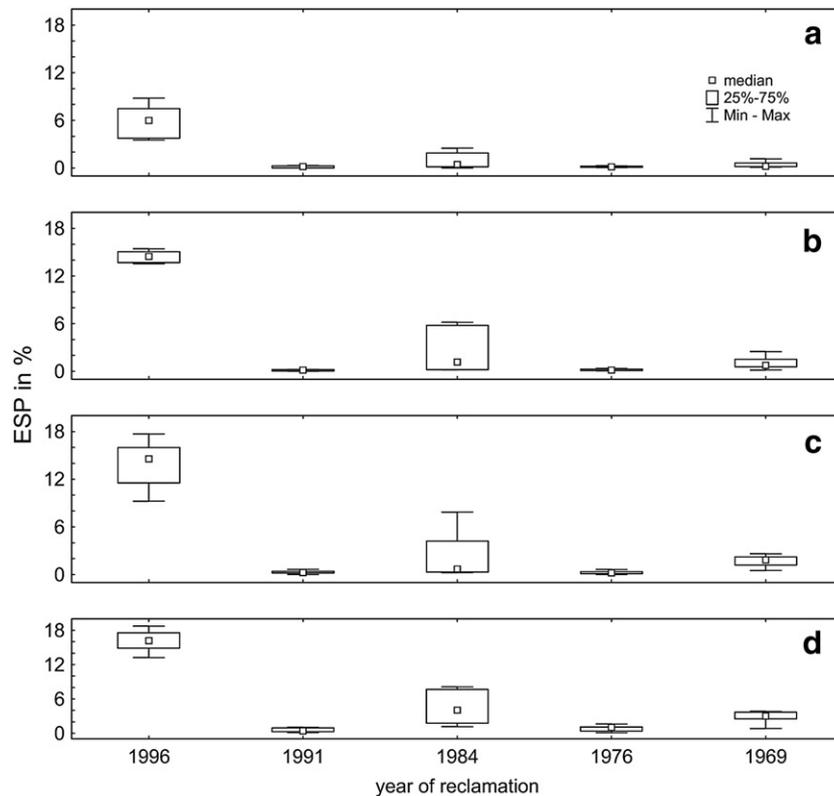


Fig. 2. ESP in all studied horizons (a: 0–10 cm, b: 10–30 cm, c: 30–60 cm and d: 60–90 cm) and sites, reclaimed in 1969, 1976, 1984, 1991 and 1996.

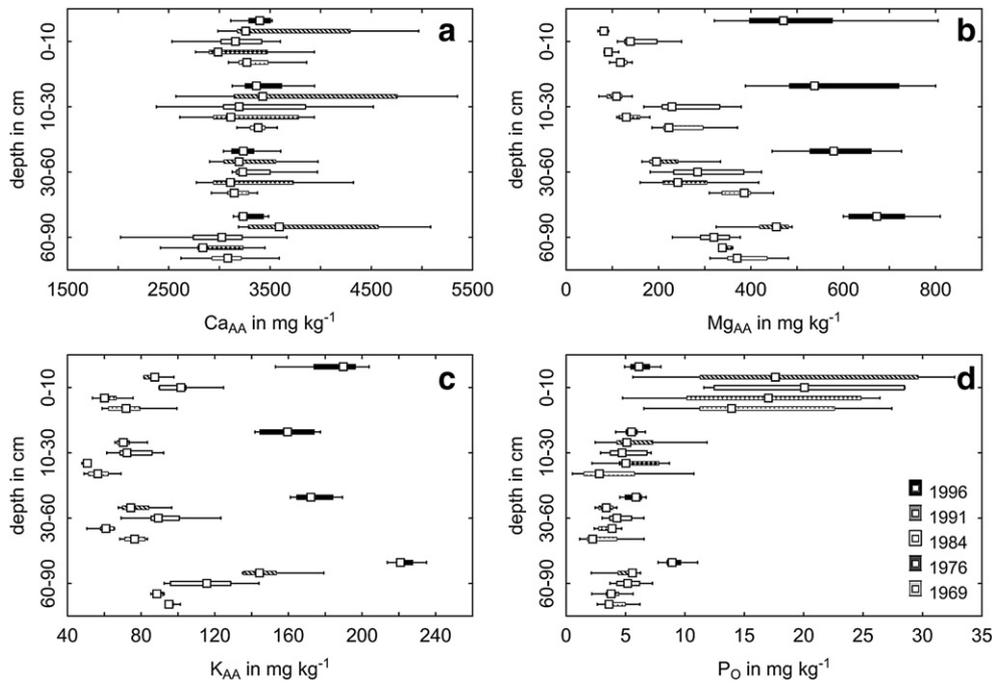


Fig. 3. Ca_{AA} (a), Mg_{AA} (b), K_{AA} (c) and P_O (d) contents in four depths of the studied soils diked in 1969, 1976, 1984, 1991 and 1996.

than below (Table 1). With respect to all studied sites and soil depths, Ca_t ranged between 18.7 and 23.3 $g\ kg^{-1}$ (Fig. 1a). In the lower three horizons Ca_t was significantly correlated with time since reclamation started ($r_s=0.9$), but not in 0–10 cm. Contrarily, Mg_t decreased only slightly along the chronosequence and ranged between 9.1 and 10.9 $g\ kg^{-1}$ (Fig. 1b). Total potassium content ranged between 2.43 and 3.43 $g\ kg^{-1}$ (Fig. 1c) and was not influenced during the studied period of reclamation. Total phosphorus content ranged from 335 to 671 $mg\ kg^{-1}$. In 0–10 cm and 60–90 cm P_t significantly increased along the chronosequence ($r_s=0.9$);). The ESP decreased in the three upper horizons as an effect of reclamation (Fig. 2a–c) from 6.0 to 0.2% in 0–10 cm and from more than 14 to less than 1% in 10–30 and 30–60 cm. The strongest effect was discernible comparing sites reclaimed in 1991 and 1996 i.e. during the first years of marsh soil development. However ESP decreased significantly in 0–10 ($r_s=-0.42$), 10–30 ($r_s=-0.26$) and 30–60 cm ($r_s=-0.31$). Average contents of available calcium (Ca_{AA}) ranged between 2.8 and 3.6 $g\ kg^{-1}$ (Fig. 3a) and constituted between 12.5 and 17.5% of Ca_t . Contrarily to Ca_t in none of the studied soil depths correlations between Ca_{AA} and the age of the site were detected. The soils of this study contained between 81 and 672 $mg\ Mg_{AA}\ kg^{-1}$ soil (Fig. 3b), which constituted between 0.9 and 6.5% of Mg_t . Available magnesium content decreased slightly with time after reclamation. This development was pronounced during the first years after reclamation as the drop in 0–10 cm from 471 $mg\ kg^{-1}$ in 1996 to 82 $mg\ kg^{-1}$ in 1991 and in 10–30 cm from 514 $mg\ kg^{-1}$ in 1996 to 109 $mg\ kg^{-1}$ in 1991 revealed. Contents at the older sites ranged from 90 to 230 $mg\ kg^{-1}$. K_{AA} ranged between 51 and 190 $mg\ kg^{-1}$ and therefore accounted for 2 to 7.1% of K_t . As for magnesium, large differences in K_{AA} observed between 1996

and 1991 revealed that the decrease of K_{AA} was most pronounced during the first 10 years after reclamation (Fig. 3c). Available P (P_O) ranged from 2.2 to 20.1 $mg\ kg^{-1}$ (Fig. 3d), which accounted for less than 4% of P_t . Sites reclaimed between 1969 and 1991, which were already cultivated, showed contents between 14 and 20 $mg\ kg^{-1}$ in 0–10 but only 3–5 $mg\ kg^{-1}$ in 10–30 cm. This large difference between P_O in both depths revealed that P_O was unequally distributed in the topsoil. In contrast, the more recently reclaimed site showed P_O ranging from 5.5 to 8.9 $mg\ kg^{-1}$. These observations reveal that P_O increased essentially in the first 10 cm in these reclaimed marsh soils. By contrast, in deeper horizons P_O decreased at increased times of reclamation ($r_s=-0.82$ in 30–60 cm and $r_s=-0.71$ and 60–90 cm).

4. Discussion

The nutritional status of Hangzhou Bay waters and therefore of the reclaimed land is influenced by the nutrient loads of the Yangtze (Yan and Zhang, 2003). In this study, the youngest site represents soil conditions four years after embankment without any other use. Only minor differences in texture (with the exception of 1991) and similar values of Ca_t , Mg_t , K_t as well as P_t among the sites studied suggest that the sediments that formed the studied sites are comparable. Main soil forming processes in recently reclaimed soils are dewatering, subsidence, desalinisation and decalcification (Mueller-Althen, 1994b; Portnoy, 1999; Giani and Landt, 2000). Iron-sulphides are oxidized by soil air oxygen and soil micro organisms produce iron-oxides and sulphuric acid. The latter is neutralized by the soil carbonates and adequate amounts of carbonate are dissolved and Ca is leached. As a consequence, Ca^{2+} is released

into the soil solution and replaces Na^+ at the exchange sites (Quadir et al., 2003). Rapid desalinisation in the study area is supported by the high annual precipitation of about 1300 mm (Shi et al., 2002) and lateral transport of drainage water through canals across the reclaimed area. From the fact, that the most recent soil has higher EC_E values it is assumed that rapid desalinisation is supported by the rapid decrease in EC_E during the initial reclamation. Rapid desalinisation is also supported by significant decreases of ESP in the upper horizons. Comparatively high ESP in all depths of the site reclaimed in 1984 support the assumption that capillary rise influences element concentrations in the mineral soil, as this site was situated close to one of the draining canals. Contrarily to desalinisation, decalcification appeared to be less intensive. In the present study, decreasing Ca_t and carbonate contents in 0–10 cm only indicated an initial decalcification of the topsoil that can be related to decreasing SOC contents in all studied depths. Lowering of the water table and aeration as a result of diking and intensive drainage of the sediments led to an accelerated decomposition of the organic matter and thereby to declining SOC. The significant positive correlation of Ca_t with time after reclamation started in the deeper horizons ($r_s = -0.9$ for 10–30, 30–60 and 60–90 cm) may be attributed to leaching of soluble $\text{Ca}(\text{HCO}_3)_2$ and to precipitation of carbonates under conditions of lower CO_2 -saturation of the soil solution.

Ca_{AA} , which represents soluble and exchangeable forms of this element (Warncke and Brown, 1998), is considered readily available for plant uptake. In the studied alkaline soils Ca_{AA} may slightly overestimate the available pool. However the slow decrease of Ca_{AA} within 31 years after reclamation, intensive agricultural use and drainage, reveals a replenishment of the available Ca pool from not available forms. These findings are in good accordance with the general assumption, that availability of calcium in calcareous soils and marshes is not limiting plant growth (Haby, 1990; Warncke and Brown, 1998). It is assumed that the observed strong initial decline of Mg_{AA} between four and nine years after embankment is attributed to leaching of easily soluble Mg-bearing salts, that were accumulated within the sediments and constitute a source for Mg_{AA} . This decline accounted for a total loss in Mg_{AA} of 1600 kg ha^{-1} in the top 30 cm. Additional displacement of magnesium at the exchange sites by calcium due to carbonates solubilisation may also have contributed to decreasing Mg_{AA} (Blume and Stahr, 1995; Grattan and Grieve, 1999). The comparatively steady level of Mg_{AA} in the studied soils during the first three decades after embankment indicates that the pool of available magnesium is replenished at a high rate for maintaining proper plant growth. Furthermore, Mg_t in all depths is considered very high according to soil standards (Schlichting et al., 1995) and provides an accurate pool for plant nutrition that will be rendered available through weathering.

According to Cox et al. (1999), K_{AA} in sites reclaimed since 1969, 1976 and 1991 was below critical values for accurate plant supply at all depth units. Total potassium content in the studied soils ranged at medium to elevated levels (Schlichting et al., 1995) and the weathering of K-containing minerals is assumed to replenish pools of K_{AA} , which may explain the slight decline of K_t in the topsoils studied. Neither K_t nor K_{AA} showed a

significant correlation with soil depth in any of the studied sites. One reason for the strong initial decline of K_{AA} may be related to the high activity of calcium in the soil solution and thus to the displacement of K at the exchange sites. Furthermore, intensive agricultural use started about four years after embankment and the following increased plant uptake of potassium and crop removal contributed to this depletion (Khan and Fenton, 1996). The fact that K_{AA} in the sites studied were below the critical values for fertilizer response given by Cox et al. (1999), suggests potassium fertilization as a convenient tool of agriculture under the given conditions. P_O represents short-term available P (Sharpley, 1987) and is considered immediately available for plant uptake (McGechan, 2002). Sims (2000) considers $10 \text{ mg P}_O \text{ kg}^{-1}$ as sufficient for optimum growth of crops. Consequently, only in 0–10 cm of all sites except the one reclaimed in 1996, P_O can be presumed as adequate for crop growth. Very low P_O in 0–10 cm of site reclaimed in 1996, where agricultural use had not yet commenced, allows the assumption that older sites had been fertilized. The studied soils contain high Ca, thus it is probable that a significant portion of P applied will be precipitated as low soluble Ca phosphates (Delgado and Torrent, 2000; Domínguez et al., 2001; McGechan, 2002). The mobility and availability of applied fertilizer is reduced to a minimum in the presence of a high Ca activity in the soil solution (Bowman and Savory, 1992; Samadi and Gilkes, 1999). High contents of calcium throughout all sites studied and depths are likely to promote the precipitation of insoluble calcium phosphates and consequently the reduction of soluble and surface-sorbed P (Afif et al., 1993; Domínguez et al., 2001; McGechan, 2002). Increasing P_t must therefore be considered a result of excess fertilizer application (Sharpley and Withers, 1994). For soils of varying acidity Fardeau (1995) reports a percentage of up to 15% fertilizer P that is utilized by crops after application of the fertilizer. A part of the applied fertilizer is adsorbed to surface sites and contributes to plant availability of phosphorus. Available P contents can also be replenished by gradual conversion of calcium phosphates into plant available forms (McGechan, 2002). This process is enhanced by decreasing P concentration in the soil solution due to plant absorption. However as P availability on saline soils generally is reduced (Sharpley and Withers, 1994) and even though fertilizer P is not recovered in the available pool, P fertilization appears necessary to sustain intensive agricultural use. In the long term decalcification and acidification will lead to enhanced mobility and availability of the high P_t stocks (Portnoy and Giblin, 1997). Further considerations of the status of available P and a potential risk of drainage and loss of phosphate and therefore pollution of freshwater with ongoing development of the soils studied should also include monitoring of the nutrient status of the Yangtze and its tributaries. Liu et al. (2003) suggest that concentrations of nutrients in the Yangtze and its tributaries will further increase due to ongoing intensification of agricultural production and use of fertilizers, especially after the completion of the Three Gorges Dam. Therefore, if the described way of land reclamation will be of further importance, contents of available phosphorus, as well of nitrate, should be monitored carefully before application of fertilizers.

5. Conclusions

During the initial period of pedogenesis of saline marsh soils after artificial geogenesis and under intensive drainage management processes well established for naturally developed marshes were observed. Most evident were desalinisation. Decalcification had just started and was detectable in the topsoil only and intensive acidification had not yet occurred. As in natural marshes, decline of soil organic matter was observed as a result of mineralization after dewatering and aeration of the substrate.

Available calcium and magnesium were considered accurate for intensive agricultural production. For intensive agricultural use and high crops, potassium fertilization may be useful. Due to the low availability index, phosphorus fertilization appears necessary for agricultural use. Total contents of calcium, magnesium, potassium and phosphorus are considered to support replenishment of available pools with further pedogenesis. The described way of artificial land reclamation represents an important method for alleviating population density in the coastal zones of Zhejiang Province (P.R. China), but intensive management, that includes drainage and K and P fertilization is necessary to sustain high crop yields.

Acknowledgments

We thank the *Sächsische Landesanstalt für Forsten* for their friendly support by conducting the analysis of total Mg, Ca, K and P contents. The authors gratefully acknowledge the Federal Ministry of Education and Research for the financial support of the project “Sustainable Agroforestry in Saline Soils of Zhejiang Province, P.R. China” (FKZ: 0339742).

References

- Afif, E., Matar, A., Torrent, J., 1993. Availability of phosphate applied to calcareous soils of West Asia and North Africa. *Soil Sci. Soc. Am. J.* 57, 756–760.
- Blume, H.-P., Stahr, K., 1995. In: Schlichting, E., Blume, H.-P., Stahr, K. (Eds.), *Bodenkundliches Praktikum*, 2nd edition. Blackwell Wissenschaftsverlag, Berlin Wien.
- Bowman, R.A., Savory, D.J., 1992. Phosphorus distribution in calcareous soil profiles of the Central Plains. *Soil Sci. Soc. Am. J.* 56, 423–426.
- Bruemmer, G., Grunwaldt, H.-S., Schroeder, D., 1971. Beiträge zur Genese und Klassifizierung der Marschen. II. Zur Schwefelmetabolik in Schlicker und Salzmarschen. *J. Plant Nutr. Soil Sci.* 128, 208–220.
- Chen, Z., Kostaschuk, R., Yang, M., 2001. Heavy metals on tidal flats in the Yangtze Estuary, China. *Environ. Geol.* 40, 479–742.
- Cox, A.E., Joern, B.C., Brouder, S.M., Gao, D., 1999. Plant-available potassium assessment with a modified sodium tetraphenylboron method. *Soil Sci. Soc. Am. J.* 63, 902–911.
- Delgado, A., Torrent, J., 2000. Phosphorus forms and desorption patterns in heavily fertilized calcareous and limed acid soils. *Soil Sci. Soc. Am. J.* 64, 2031–2037.
- Domínguez, R., Del Campillo, C., Peña, F., Delgado, A., 2001. Effect of soil properties and reclamation practices on phosphorus dynamics in reclaimed calcareous marsh soils from the Guadalquivir Valley, SW Spain. *Arid Land Res. Manag.* 15, 203–221.
- Fardeau, J.C., 1995. Dynamics of phosphate in soils. An isotopic outlook. *Nutr. Cycl. Agroecosyst.* 45, 91–100.
- Frank, K., Beegle, D., Denning, J., 1998. Phosphorus. In: Brown, J.R. (Ed.), *Recommended Soil Test Procedures*. North Central Regional Research Publication, vol. 221, pp. 21–30.
- Giani, L., Landt, A., 2000. Initial marsh soil development from brackish sediments. *J. Plant Nutr. Soil Sci.* 163, 549–553.
- Giani, L., Ahrens, V., Duntze, O., Kruse Imer, S., 2003. Geo-pedogenesis of salic Fluvisols on the North Sea island of Spiekeroog. *J. Plant Nutr. Soil Sci.* 166, 370–378.
- Grattan, S.R., Grieve, C.M., 1999. Salinity–mineral relations in horticultural crops. *Sci. Hortic.* 78, 127–157.
- Haby, V.A., 1990. Testing soils for potassium, calcium and magnesium, In: Westerman, R.L. (Ed.), *Soil testing and plant analysis*, 3rd edition. Soil Sci. Soc. Am., Book Series, vol. 3. SSSA, Madison, WI, pp. 181–227.
- ISO 11466, 1995. *Soil Quality — Extraction of Trace Elements Soluble in Aqua Regia*. International Organization for Standardization. Geneva, Switzerland.
- Khan, F.A., Fenton, T.E., 1996. Factors affecting potassium status of alluvial-derived soils of Western Iowa. *Soil Sci. Soc. Am. J.* 60, 836–842.
- Liu, M., Hou, L., Xu, S., Ou, D., Yang, Y., Zhang, B., Liu, Q., 2002. Adsorption of phosphate on tidal flat surface sediments from the Yangtze estuary. *Environ. Geol.* 42, 657–665.
- Liu, S.M., Zhang, J., Chen, H.T., Wu, Y., Xiong, H., Zhang, Z.F., 2003. Nutrients in the Changjiang and its tributaries. *Biogeochemistry* 62, 1–18.
- McGechan, M.B., 2002. Sorption of phosphorus by soil, part 2: measurement methods, results and model parameter values. *Biosyst. Eng.* 82, 115–130.
- Mueller-Ahlten, W., 1994a. On the genesis of tidal marsh soils. I. The influence of sediment-and soil structure. *J. Plant Nutr. Soil Sci.* 157, 1–9.
- Mueller-Ahlten, W., 1994b. On the genesis of tidal marsh soils. II. Carbonate sedimentation, decalcification. *J. Plant Nutr. Soil Sci.* 157, 333–343.
- Portnoy, J.W., 1999. Salt marsh diking and restoration: biochemical implications of altered wetland hydrology. *Environ. Manag.* 24, 111–120.
- Portnoy, J.W., Giblin, A.E., 1997. Effects of historic tidal restrictions on salt marsh sediment chemistry. *Biogeochemistry* 36, 275–303.
- Quadir, M., Steffens, D., Yan, F., Schubert, S., 2003. Proton release by N₂-fixing plant roots: a possible contribution to phytoremediation of calcareous sodic soils. *J. Plant Nutr. Soil Sci.* 166, 14–22.
- Richards, L.A. (Ed.), 1954. *Diagnosis and Improvement of Saline and Alkali Soils*. Agricultural Handbook, vol. 60. U.S. Government Printing Office, Washington D.C.
- Samadi, A., Gilkes, R.J., 1999. Phosphorus transformations and their relationships with calcareous soil properties of Southern Western Australia. *Soil Sci. Soc. Am. J.* 63, 809–815.
- Schlichting, E., Blume, H.-P., Stahr, K., 1985. *Bodenkundliches Praktikum*, 2nd edition. Blackwell Wissenschaftsverlag, Berlin Wien.
- Schroeder, D., Bruemmer, G., 1969. Beiträge zur Genese und Klassifizierung der Marschen. I. Problematik der Marschen-Genese und -Klassifizierung und Untersuchungen zum Ca/Mg-Verhältnis. *J. Plant Nutr. Soil Sci.* 122, 220–249.
- Sharpley, A.N., 1987. The kinetics of soil potassium desorption. *Soil Sci. Soc. Am. J.* 51, 912–917.
- Sharpley, A.N., Withers, P.J.A., 1994. The environmentally-sound management of agricultural phosphorus. *Fert. Res.* 39, 133–146.
- Shi, Z., Wang, R., Huang, M.X., Landgraf, D., 2002. Detection of coastal saline land uses with multi-temporal Landsat images in Shangyu City, China. *Environ. Manag.* 30, 142–150.
- Sims, T., 2000. Soil test phosphorus. In: Pierzynski, G.M., Sharpley, A.N. (Eds.), *Methods of Phosphorus Analysis for Soils, Sediments, Residuals and Waters*. Southern Cooperative Series Bulletin, vol. 396, pp. 13–23.
- Warncke, D., Brown, J.R., 1998. Potassium and other basic cations. In: Brown, J.R. (Ed.), *Recommended Soil Test Procedures*. North Central Regional Research Publication, vol. 221, pp. 31–33.
- Yan, W., Zhang, S., 2003. The composition and bioavailability of phosphorus through the Changjiang (Yangtze) River during the 1998 flood. *Biogeochemistry* 65, 179–194.